LONG-TERM DEMONSTRATION OF SORBENT ENHANCEMENT ADDITIVE TECHNOLOGY FOR MERCURY CONTROL

Final Technical Report

(for the period May 31, 2006, through May 27, 2011)

Prepared for:

AAD Document Control

U.S. Department of Energy
National Energy Technology Laboratory
626 Cochrans Mill Road
PO Box 10940, MS 921-107
Pittsburgh, PA 15236-0940

Cooperative Agreement No.: DE-FC26-06NT42775

Prepared by:

Jason D. Laumb
Dennis L. Laudal
Grant E. Dunham
John P. Kay
Christopher L. Martin
Jeffrey S. Thompson
Nicholas B. Lentz
Alexander Azenkeng
Kevin C. Galbreath
Lucinda L. Hamre

Energy & Environmental Research Center
University of North Dakota
15 North 23rd Street, Stop 9018
Grand Forks, ND 58202-9018

2011-EERC-05-05 May 2011

DISCLAIMER

EERC DISCLAIMER

LONG-TERM DEMONSTRATION OF SORBENT ENHANCEMENT ADDITIVE TECHNOLOGY FOR MERCURY CONTROL

ABSTRACT

Long-term demonstration tests of advanced sorbent enhancement additive (SEA) technologies have been completed at five coal-fired power plants. The targeted removal rate was 90% from baseline conditions at all five stations. The plants included Hawthorn Unit 5, Mill Creek Unit 4, San Miguel Unit 1, Centralia Unit 2, and Hoot Lake Unit 2. The materials tested included powdered activated carbon, treated carbon, scrubber additives, and SEAs. In only one case (San Miguel) was >90% removal not attainable. The reemission of mercury from the scrubber at this facility prevented >90% capture.

TABLE OF CONTENTS

LIST OF FIGURES iii

LIST OF TABLES v

EXECUTIVE SUMMARY vi

INTRODUCTION 1

EXPERIMENTAL METHODS 3
- Control Technologies 4
- PAC Injection 4
- SEA Injection 6
- Reemission Additives 6
- Unit Configurations 7
  - Kansas City Power & Light Hawthorn Unit 5 7
  - Louisville Gas & Electric's Mill Creek Unit 4 7
  - San Miguel Generating Station Unit 1 7
  - Centralia Generating Station Unit 2 7
  - Hoot Lake Unit 2 9
- Sampling Methods 11
- Mercury Sampling 11
- Sorbent Traps 13
- Solids and Liquids Sampling 14
  - Trace Metal and Particulate Sampling 14
- ICR Sampling 14
- CCP Mineralogical Analysis Methods 15
- Preparation of Paste Mixtures 16
- Leaching Studies 17

RESULTS AND DISCUSSION 17
- Hawthorn Unit 5 18
- Mill Creek Unit 4 19
- San Miguel Unit 1 20
- Centralia Unit 2 24
  - Parametric Testing 24
- Extended Testing 26
- Alternate SEA Testing 27
- Comparison of Alternate SEA Technology 28
- Hoot Lake Unit 2 30

Continued…

TABLE OF CONTENTS (continued)

BALANCE-OF-PLANT RESULTS 31
  ICR Testing 33
  Analysis of Mineralogy in CCPs 34
    Prepare Mortar or Paste Mixtures 34
    Leach Mercury Emission Control and Corresponding Standard CCPs 37
    Alter the pH of the Leaching Solution with 1 N Potassium Hydroxide 40
    Analyze Mercury Emission Control and Corresponding Standard CCPs 41

CONCLUSIONS 44
  Mill Creek 4 44
  Hawthorn 5 45
  San Miguel 1 46
  Centralia 2 46
  Hoot Lake 2 47
  CCP Analysis 48

REFERENCES 50

LONG-TERM DEMONSTRATION OF SORBENT ENHANCEMENT ADDITIVE TECHNOLOGY FOR MERCURY CONTROL – HAWTHORN .... Appendix A

LONG-TERM DEMONSTRATION OF SORBENT ENHANCEMENT ADDITIVE TECHNOLOGY FOR MERCURY CONTROL – SAN MIGUEL .... Appendix B

FULL-SCALE TESTING TO EVALUATE MERCURY CONTROL OPTIONS AT THE CENTRALIA GENERATING STATION .... Appendix C

FULL-SCALE MERCURY CONTROL DEMONSTRATIONS: ICR SAMPLING WITH MERCURY CONTROL .... Appendix D

LIST OF FIGURES

1 Schematic of activated carbon injection system 5

2 Schematic of HAW5 showing SEA/PAC injection points and sampling locations 8

3 Schematic of MC4 showing SEA/PAC injection points and sampling locations 8

4 SM1 schematic showing injection and sampling locations 9

5 Schematic of Cent2 10

6 Schematic of HL2 showing injection and sampling locations 10

7 Hourly average CMM-based mercury removal and CMM data at the ESP and FGD outlets 21

8 Plot of mercury removal efficiencies obtained at MC4 during long-term testing over a period of 1-month 21

9 Mercury concentration of the liquid portions of the FGD slurry samples during baseline and long-term testing 22

10 ID fan outlet and stack percent mercury removals as a function of DARCO Hg-LH injection rates 25

11 Summary of SF10–SB24 extended test mercury removal data 27

12 SC1–SB24 extended test CMM data 29

13 Summary of alternate SEA injection results compared to other technologies tested 29

14 Stack percent mercury removals as a function of parametric SF10–SB24 injection rates 30

15 Standard fly ash–cement paste cylinder 35

16 Cement paste with fly ash containing AC 36

17 Cement paste with fly ash, AC, and SEA4 37

18 SEM image of standard fly ash after 30-day LTL 39

Continued…

LIST OF FIGURES (continued)

19 SEM image of Hg control CCP after 30-day LTL 39

20 Fly ash after 24 hours of hydration at natural pH showing ettringite formation................. 41

21 Fly ash after 24 hours of hydration with leaching solution containing 1 N KOH 42

22 SEM image of the as-received standard fly ash 43

23 SEM image of as-received Hg control CCP.. 44

LIST OF TABLES

1 Brief Descriptions of the Units Selected for the Tests 3

2 Injected Sorbents 5

3 SEAs Injected 6

4 Sampling Methods 11

5 Solids and Liquids Sample Collection 15

6 Sample Analysis 15

7 Test Matrix for ICR Sampling at HL2 16

8 Comparison of the Performances of the Various Additives Tested at HAW5 18

9 Summary of the Results of Parametric Tests at MC4 19

10 Summary of the Results of Parametric Tests at SM1 23

11 Summary of the Results of Parametric Tests at Cent2 25

12 Extended Test Mercury Removals at the Stack 27

13 Summary of Alternative SEA Performance 28

14 Chemical Analyses of Specific Points from the Standard Fly Ash–Cement Paste 35

15 Chemical Composition of Particles from the Fly Ash and AC–Cement Paste Sample 36

16 Chemical Composition of Particles Represented in the Fly Ash, AC, and SEA4–Cement Paste Sample 37

17 Particle Chemistry of Fly Ash after 24 hours of Hydration at Natural pH by EDS 41

18 Chemical Compositions of Fly Ash Particles after 24 hours of Hydration with Leaching Solution Containing 1 N KOH by EDS 42

19 Particle Chemistries of As-Received Standard Fly Ash by EDS 43

20 Particle Chemistry of As-Received Hg Control CCP by EDS 44

LONG-TERM DEMONSTRATION OF SORBENT ENHANCEMENT ADDITIVE TECHNOLOGY FOR MERCURY CONTROL

EXECUTIVE SUMMARY

Long-term demonstration tests of advanced sorbent enhancement additive (SEA) technologies have been completed at five coal-fired power plants. The targeted removal rate was 90% from baseline conditions at all five stations. The plants included Hawthorn Unit 5, Mill Creek Unit 4 (MC4), San Miguel Unit 1, Centralia Unit 2, and Hoot Lake Unit 2. The materials tested included powdered activated carbon, treated carbon, scrubber additives, and SEAs. In only one case (San Miguel) was >90% removal not attainable. The reemission of mercury from the scrubber at this facility prevented >90% capture. In all cases, mercury measurement took place at the stack.

Baseline tests, followed by a suite of parametric tests, were conducted at the MC4 Station in June 2007. It was found that the Babcock & Wilcox (B&W) additive added at the rate of 80 g/hr was capable of achieving >90% Hg removal from both baseline and from coal Hg levels. This technology was used for a 1-month, long-term study, and the average mercury removal efficiency of 91.8% was sustained without undue complications to the plant's operation. Overall, the amount of reemission observed at MC4 was significantly lower than previously reported. Powdered activated carbon (PAC) did not show any measurable improvement on the capture of mercury. This is not particularly surprising, since the coal has a high chlorine content, which combines with char to effect most of the elemental mercury oxidation that chlorine/PAC would be doing if the coal were low in chlorine content. In addition to continuous mercury monitor (CMM) and Ontario Hydro (OH) measurements, U.S. Environmental Protection Agency (EPA) Method 30B (sorbent trap) measurements were also obtained for comparison with the CMM and OH data.

At Hawthorn Unit 5, results of the parametric tests revealed that two possible technologies are capable of achieving more than 90% mercury removal from baseline and from coal mercury levels. These include addition of PAC (2 lb/Macf) in combination with Cl_2 (500 ppm) and the Norit DARCO® Hg-LH additive (3 lb/Macf), which showed performances of 94% and 93%, respectively, from coal mercury levels (93% and 90%, respectively, from baseline mercury levels). Furthermore, addition of PAC (322 lb/hr) in conjunction with Cl_2 (1200 ppm) and the DARCO Hg-LH (2 lb/Macf) each afforded 89% removal from coal mercury levels, and each of these was only about 3% short of 90% removal from baseline.

At the San Miguel Station, scrubber reemission remains a critical problem for the San Miguel Electric Cooperative (SMEC) power plant and prevents the plant from obtaining a mercury capture of ≥90%. The B&W scrubber additive tested demonstrated little to no effect on scrubber emission compared to the data obtained in the absence of scrubber additive.

The SF11–SB11 technology provided by RLP Energy (currently Midwest Emission Control Corporation) demonstrated an 81.7% mercury removal across the plant at SF11 and SB11 injection rates of 80 lb/hr and 3.5 lb/Macf. This technology achieved results slightly better than other materials tested at SMEC and offers the potential to achieve ≥90% mercury capture if the scrubber reemission can be mitigated.

At Centralia Unit 2, baseline, parametric, and extended tests were successfully conducted at the test unit for several mercury control technologies. The baseline test period indicated that the flue gas mercury concentration exhibits some variance but remains within a consistent range. Parametric test results indicated that SF10–SB24, SF10–SB21, and DARCO Hg-LH were able to achieve the target mercury removal of ≥ 80%. Because of its strong performance, SF10–SB24 was chosen for four extended tests, which targeted mercury removals of 60%, 70%, 80%, and >90%. The targeted mercury removal was exceeded for each of the extended tests.

During SF10–SB24 injection, the Lodge electrostatic precipitators (ESPs) captured most of the flue gas mercury with an additional 5%–15% capture across the scrubber. During SF10–SB24 ET3, approximately 6.7% of the mercury was removed in the Koppers ESPs, 71.1% across the Lodge ESPs, and 16.8% across the scrubber for a total mercury removal of 94.6% based on mass balance calculations. Since the majority of the mercury is removed in the Lodge ESPs before it enters the scrubber, the total mercury in the scrubber and flue gas desulfurization (FGD) material decreases because of less mercury entering the scrubber as compared to baseline conditions. This is beneficial when FGD materials are considered as a salable commodity.

The Information Collection Request (ICR) requirements for the Hoot Lake Plant Unit 2 were successfully met. The data were compiled, entered into the EPA electronic reporting tool (ERT) and submitted to EPA August 2010. This site was especially challenging because of plant configuration and port placement, but the challenges were overcome. In addition, a mercury control technology provided by Grünergy Technologies was parametrically tested for its effectiveness. Results indicate that a mercury removal rate of 75% can be achieved across the ESP with the combination of a sorbent injection rate of 1.71 lb/Macf upstream of the air heater and an additive injection rate of 0.34 lb/Macf into the boiler. It was determined that 85% reduction can be achieved with a combined injection of sorbent/additive of 2.35/0.47 lb/Macf, respectively. Greater than 90% removal can be attained but would require sorbent/additive injection rates above 4.27/0.85 lb/Macf, respectively. There have been anecdotal observations of particulate loading decrease across an ESP at a few other plants, but data have not been presented to the public to date. Metallic hazard air pollutant concentrations varied widely but did seem to indicate that beryllium and cobalt did decrease. Selenium, however, appeared to increase. As expected, mercury concentrations decreased.

The coal combustion product (CCP) analysis indicates that additives utilized for mercury emission control can be detrimental to the use of fly ash as a cement replacement in concrete. Two mercury control test demonstration CCPs that passed ASTM International C618 physical testing in a previous study exhibited cementitious reactions in paste form similar to the standard fly ash. Previous synthetic groundwater leaching procedure and long-term leaching profiles showed a shift from decreasing trace element concentrations over time from a standard fly ash to increasing concentrations over time from a corresponding mercury control testing CCP. The leaching profile provided indirect evidence that ettringite formation was responsible for the reduction in concentrations in the standard fly ash. These samples were leached again, with results showing a significant decrease in the amount of ettringite present in the sample from mercury emission control testing, supporting the previous hypothesis. The addition of 1 N KOH, intended to increase the leachate pH of a material to 12, altered the leaching trend noted in some CCPs previously evaluated at the EERC. The results implied inhibited ettringite formation. One sample was chosen for mineralogical analyses following leaching at the natural pH with distilled, deionized water and with the addition of 1 N KOH. The results showed a significant amount of ettringite formation in the natural pH sample, while limited ettringite formation was evident in the sample with the addition of 1 N KOH. An excessive pH increase and the presence of K contributed to the reduced level of ettringite formation. An as-received mercury control testing CCP and the corresponding standard CCP were analyzed for mineralogical differences. Chemical compositions of particles show little difference between the two samples.

LONG-TERM DEMONSTRATION OF SORBENT ENHANCEMENT ADDITIVE TECHNOLOGY FOR MERCURY CONTROL

INTRODUCTION

In North America, testing has been under way at coal-fired electric power plants to find viable and economical mercury control strategies to meet pending regulations. The U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL) implemented a program focused on technology development and testing that would provide significant mercury reduction. Several entities, including the Energy & Environmental Research Center (EERC), NETL, other research groups, technology providers, and electric generation companies have dedicated significant resources to work with industry and the federal government to study the fate and formation of mercury in coal-fired electric generation power plants, providing significant advances in understanding and developing control technologies.

The primary goal of these test programs was to identify sorbent-based technology options that could be used to meet an overall mercury removal goal of 80%–90%. The technology that presently holds the most promise to meet U.S. regulations for mercury control is injection of activated carbon (AC) into the flue gas stream—both with and without enhancement additives that help promote Hg oxidation and/or capture. Elemental mercury (Hg^0) can be difficult to capture with existing control technologies. Therefore, oxidizing agents and sorbent enhancement additives (SEAs) are being considered as part of an overall control strategy for power plants firing coals that produce predominantly elemental mercury in the flue gas stream. The EERC has been developing and testing advanced mercury control technologies for power plants firing coals for the past 20 years. Projects funded by the U.S. Environmental Protection Agency (EPA) through the EERC's Center for Air Toxic Metals® (CATM®) (1–4) and those funded jointly by the industry and DOE on lignite (5) and subbituminous coals (6) have led to greater experience in the development and testing of new SEA technologies for mercury control. Many large-scale studies involving SEAs have been conducted which show significant improvement in mercury capture (7–9). Under this program, full-scale mercury control tests have been carried out at five power generation stations:

- Kansas City Power & Light's (KCP&L) Hawthorn Unit 5 (HAW5) located near Kansas City, Missouri.
- Louisville Gas & Electric's (LG&E) Mill Creek Unit 4 (MC4) located near Louisville, Kentucky.
- San Miguel Electric Cooperative (SMEC) San Miguel Generating Station Unit 1 (SM1) located near Christine, Texas.
- TransAlta's Centralia Generating Station Unit 2 (CENT2), located near Centralia, Washington.

- Otter Tail Power's Hoot Lake Plant Unit 2 (HL2), located near Fergus Falls, Minnesota.

The choice of these units was carefully made so as to provide an opportunity to test available technologies on coals with different characteristics or properties and plants with different configurations. Brief descriptions of these plants are given in Table 1. The Hawthorn, Centralia, and Hoot Lake units burn subbituminous coals which produce predominantly elemental mercury, and the Mill Creek unit burns eastern bituminous coals, which have higher levels of oxidized and particulate forms of mercury. The Texas lignite burned in the San Miguel unit also produces mostly elemental mercury. A complete description and discussion of the coals used can be found in the site-specific reports in Appendices A–D.

In addition to the evaluation of technologies for mercury control, Otter Tail Power Company's Hoot Lake Plant was randomly selected by EPA to perform Part III emissions sampling for all hazardous air pollutant (HAP) groups as part of EPA's recent Information Collection Request (ICR). The data collected from the 50 random units will have a major impact on not just mercury standards but many other constituents on the HAP list that can be affected by mercury control technologies.

The ICR is divided into three parts, with subsets of units required to report under each part. The definitions for Part III are as follows.

All facilities identified to perform stack testing shall report:

- Part III – Emission Test Data: Units identified for sampling under Part III will be required to sample for one or more of the following HAP categories for coal-fired units:
    - Acid gas HAPs (e.g., HCl and HF)
    - Dioxin/furan organic HAPs
    - Non-dioxin/furan organic HAPs
    - Mercury and other nonmercury metallic HAPs
    - Other

Much attention in this ICR is being given to the level of HAPs emitted by units without mercury control. Extensive studies have been conducted to understand trace element emissions, partitioning, and speciation in flue gas (10–15). However, the addition of mercury control technologies could impact inorganic HAPs, particulate matter (PM), or organic HAPs. The inorganic HAPs listed in the Clean Air Act Amendment of 1990 include antimony (Sb), arsenic (As), beryllium (Be), cadmium (Cd), chromium (Cr), cobalt (Co), lead (Pb), manganese (Mn), mercury (Hg), nickel (Ni), and selenium (Se). Although inorganic HAP data exist for pilot-scale and full-scale coal combustion test programs (16), very little information is available from test programs involving Hg control technologies. The organic and particulate HAPs include dioxins/furans, polycyclic organic matter (POM), volatile organic compounds (VOCs), formaldehyde, methane, and PM. Some of the units identified by EPA for this ICR do have activated carbon injection (ACI) capability. However, this still may not adequately represent what impact mercury control would have on the level of HAPs in all cases. The cobenefits and

Table 1. Brief Descriptions of the Units Selected for the Tests

Owner, Unit	Coal Type	Boiler Type, size	Particulate Control	SO_2 Control	NO_x Control	Hg Control Objective
KCP&L, HaW5	PRB Sub-bituminous	Wall-fired, 550 MW	FF	SDA[a]	LNB,[b] OFA,[c] SCR[d]	>90%
LG&E, MC4	Eastern Bituminous	Wall-fired, 530 MW	ESP	Wet FGD	LNB, SCR	>90%
San Miguel	Texas Lignite	Wall-fired, 450 MW	ESP	Wet FGD	LNB OFA	≥90%
TA, Cent2	PRB Sub-bituminous	Tangentially fired 688 MW	2 ESPs in series	Wet FGD	LNB, OFA	≥80%
OTPC, HL	PRB Sub-bituminous	Tangentially fired 54 MW	ESP	None	None	80%–85%

[a] Spray dryer absorber.
[b] Low NO_x burner.
[c] Overfire air.
[d] Selective catalytic reduction.

impacts that mercury control will have on the complete power-generating system will become more important as maximum achievable control technology (MACT) standards for all HAPs move forward. At the time of this report, only the draft National Emission Standards for Hazardous Air Pollutants (NESHAP) rules were published.

The results of this study demonstrate the usefulness of the tested technologies in achieving >80% or >90% Hg removal from baseline and/or from coal levels and are expected to be applicable to most utilities that burn subbituminous and bituminous coals in the United States and Canada. The processes tested here have also been previously proven at the pilot scale and in full-scale tests with lignite, Powder River Basin (PRB), and blended PRB–bituminous coals. These tests also demonstrate some of the challenges that can be expected with HAPs and coal combustion products (CCPs) while mercury is controlled.

EXPERIMENTAL METHODS

The methods used at each sampling site included the injection of a mercury control technology and sampling methods to determine the abundance of mercury in the flue gas. Additional sampling techniques were used at the Hoot Lake site in response to the ICR sampling. A discussion on the control technologies, unit configurations, and sampling methods follows.

Control Technologies

A number of different mercury control technologies were evaluated under this test program. The following is a brief description of each technology and the materials used with each:

- Powdered activated carbon (PAC) injection upstream of the particulate control device
- PAC injection upstream of the air heater
- PAC injection between electrostatic precipitators (ESPs)
- SEA injection into the boiler
- PAC injection upstream of the particulate control device and SEA injection into the boiler
- Halogen injection
- Scrubber additive to prevent reemission
- An alternative SEA technology

PAC Injection

Two PAC injection systems were used during this test program. The first was a portable Norit Americas, Inc., PORTA-PAC® unit, and the second was a system originally designed and manufactured by Nol-Tec. The injection systems operate on the same principle of pneumatically conveying a predetermined and adjustable amount of PAC from storage (super sacks or a silo) into the flue gas stream. The sorbent material is conveyed to the injection location in one or two heavy-duty hoses. At the injection point, the flow is divided by a flow splitter and sent to the injection lances. The injection lances are typically oriented to inject with the gas stream and at two depths in the duct. A schematic of an injection system is shown in Figure 1. A summary of the PACs used and the units at which they were used is presented in Table 2.

Three lignite coal-based AC products were provided by Norit Americas:

- DARCO® Hg is manufactured specifically for the removal of mercury in coal-fired utility flue gas emission streams.
- DARCO® Hg-LH is an impregnated lignite coal-based AC. It is intended for use in flue gas streams generated from the burning of low-halogen fuels.
- DARCO® Hg-CC is an impregnated lignite coal-based AC that was developed to minimize the impact of AC on fly ash used in the manufacture of concrete.

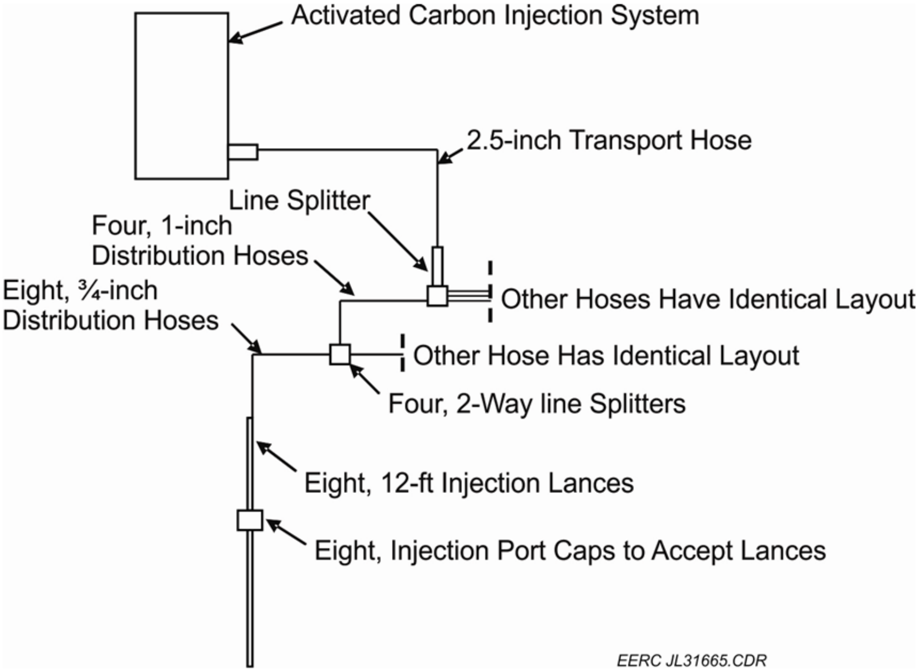


Figure 1. Schematic of ACI system.

Table 2. Injected Sorbents

Sorbent	HAW5	MC4	SM1	CENT2	HL2
DARCO Hg (Norit Americas)	X	X	X		
DARCO Hg-LH (Norit Americas)	X		X	X	
DARCO Hg-CC (Norit Americas)				X	
SB11 (RLP Energy)			X		
SB17 (RLP Energy)				X	
SB21 (RLP Energy)				X	
SB24 (RLP Energy)				X	X
SB26 (RLP Energy)			X	X	

Five types of sorbent materials were supplied by RLP Energy:

- SB11 was a carbon-based material.
- SB17 was a non-carbon-based sorbent material.
- SB21 was a carbon-based material.
- SB24 was a carbon-based material.
- SB26 was a non-carbon-based sorbent material.

Non-carbon-based sorbents were tested because of their potential concrete-compatible characteristics.

SEA Injection

Three different methods of introducing SEAs were evaluated alone or in conjunction with PAC injection. The first method involved spraying liquid SEA onto the coal as it entered the pulverizer. As the material passed through the furnace, it was dissociated, becoming available for reaction with the injected PAC or the ash in the duct. The system consisted of a holding tank, pumps, and injection nozzles. Before parametric testing began, a calibration curve was generated for each pump using the specific SEA to be injected. The injection rate was set on the skid, and it could either be maintained at a constant rate or set to follow the plant load. The second SEA injection method was carried out with a small K-Tron powder feed system consisting of a screw feeder with a 30-lb-capacity hopper. Material was carried to the injection lance by use of an eductor connected to an air supply. The material was injected directly into the boiler. A calibration curve was generated for each additive that was used to set the feed rate. During operation, the hopper was refilled as needed with material manually from 100-lb totes. The hopper was never allowed to be less than two-thirds full during the testing. The third SEA injection method (SEA2-T2) used a high-energy dissociation technology (HEDT) system to dissociate the SEA materials and treat the PAC before it was injected into the duct. With the HEDT system, the solid material is fed to a furnace where it is vaporized/dissociated and mixed with PAC. The treated carbon is then injected into the duct. For initial tests, an electric furnace was used because it could be located closer to the injection point. A second iteration of the design used a natural gas furnace located next to the PAC injection system. A summary of the SEAs injected, the units in which they were injected, the injection locations, and method of injection is presented in Table 3.

Reemission Additives

A scrubber additive supplied by Babcock & Wilcox (B&W) to prevent reemission of mercury was evaluated at Mill Creek and San Miguel. The B&W reemission additive injection skid was supplied by B&W. The injection skid, which was mounted on a trailer, consisted of a feed pump, recirculation spray, and the necessary controls to continuously pump and direct liquid out of a storage tank (in a tanker truck located near the injection skid) into the flue gas desulfurization (FGD) system.

Table 3. SEAs Injected

SEA	HAW5	MC4	SM1	CENT2	HL2
SEA1[a]	Coal				
SEA2[a]	Coal				
SEA2-T2[b]	BH[c] inlet	SCR in and out			
SF11[d]			Boiler		
SF10[d]			Boiler	Boiler	Boiler
SC1[b]				Between ESPs	
SC3[b]				Between ESPs	
SC6[b]				Between ESPs	

[a] Liquid injection onto coal.
[b] Solid dissociation with PAC injection into duct.
[c] Baghouse.
[c] Solid injection into boiler.

Unit Configurations

The five units selected for these test programs include a variety of configurations for SO_x/NO_x and particulate control. Each unit also burns a different coal(s). For complete coal and ash analysis, refer to the individual site test reports in Appendices A–D.

Kansas City Power & Light Hawthorn Unit 5 (HAW5)

KCP&L HAW5 located near Kansas City, Missouri, is a 550-MW wall-fired unit that burned a variety of PRB subbituminous coals during the test program. SCR, low-NO_x burners, and OFA are used to control NO_x emissions. The SCR catalyst was changed out during the test program. An SDA is used for SO_2 control, and a pulse-jet fabric filter baghouse is used for particulate control. The plant configuration with injection and sampling points is presented in Figure 2. At HAW5, both continuous mercury monitoring (CMM) and Ontario Hydro (OH) method sampling was performed at the SDA inlet and at the stack.

Louisville Gas & Electric's (LG&E) Mill Creek Unit 4 (MC4)

Louisville Gas & Electric's (LG&E) Mill Creek Unit 4 (MC4) located near Louisville, Kentucky is a 530 MW wall-fired unit. The MC4 unit is equipped with an SCR and low NO_x burners for NO_x control. A cold-side ESP is used for particulate control, and a wet FGD scrubber is used for SO_2 control. The plant configuration with injection and sampling points is presented in Figure 3. At MC4, both CMM and OH method sampling was performed at the ESP inlet and at the stack.

San Miguel Generating Station Unit 1 (SM1)

The San Miguel Electric Cooperative's SM1, located near Christine, Texas, is a B&W 450-MW front and rear wall-fired boiler. It is equipped with separate overfire air and low-NO_x burners for reduced NO_x emissions. A Texas lignite coal which is mined approximately 3 miles from the plant in the San Miguel Mine is used. Two parallel ESPs are used for particulate control, and a single wet FGD scrubber is used to reduce SO_x emissions. A schematic of Unit 1, with sampling and injection locations, is shown in Figure 4. The EERC installed and operated a CMM at the scrubber inlet and utilized the SMEC stack CMM throughout the duration of the testing to measure gaseous mercury concentrations in the flue gas. The CMMs were primarily used to monitor total gas-phase mercury, but adequate elemental mercury data were also collected. In addition, OH Method and sorbent trap (ST) samples were periodically collected to verify CMM instrumentation. OH method samples were also collected to obtain mercury speciation data at the scrubber inlet and stack.

Centralia Generating Station Unit 2 (CENT2)

Centralia Generating Station is owned by TransAlta Corporation and is located near Centralia, Washington. The station consists of two 688-MW units for a net generation capacity of approximately 1376 MW. Each of the units has identical tangentially fired boilers manufactured by CE. Each unit is equipped with LNBs and has OFA to reduce NO_x emissions.

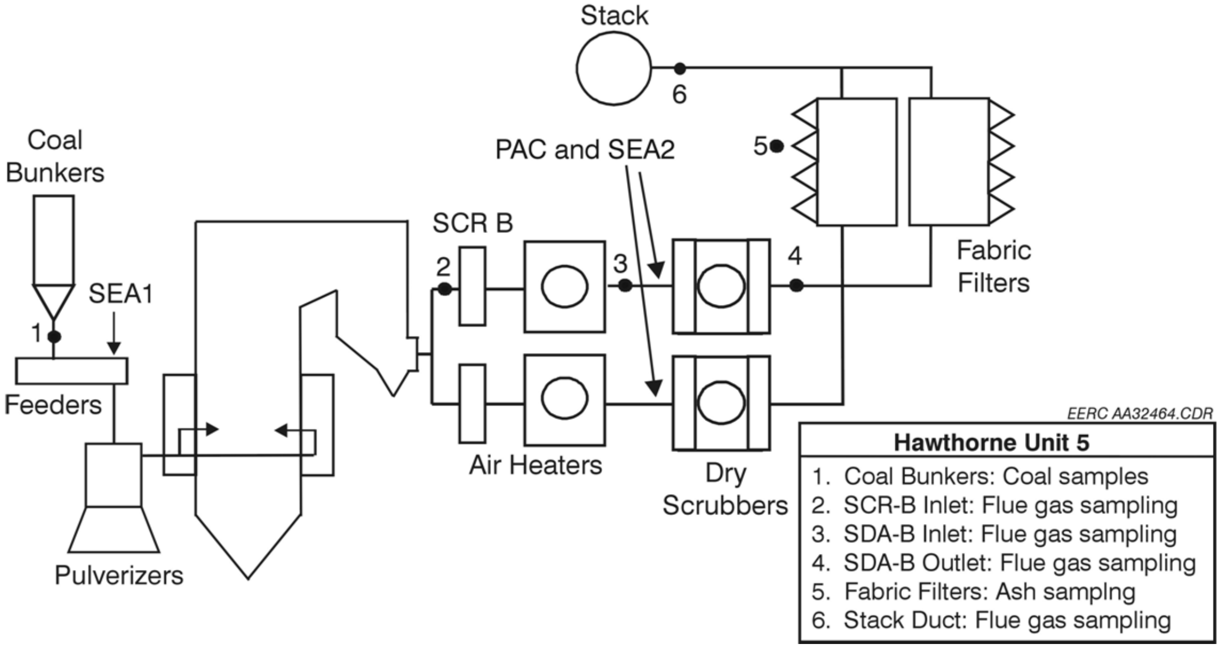


Figure 2. Schematic of HAW5 showing SEA/PAC injection points and sampling locations.

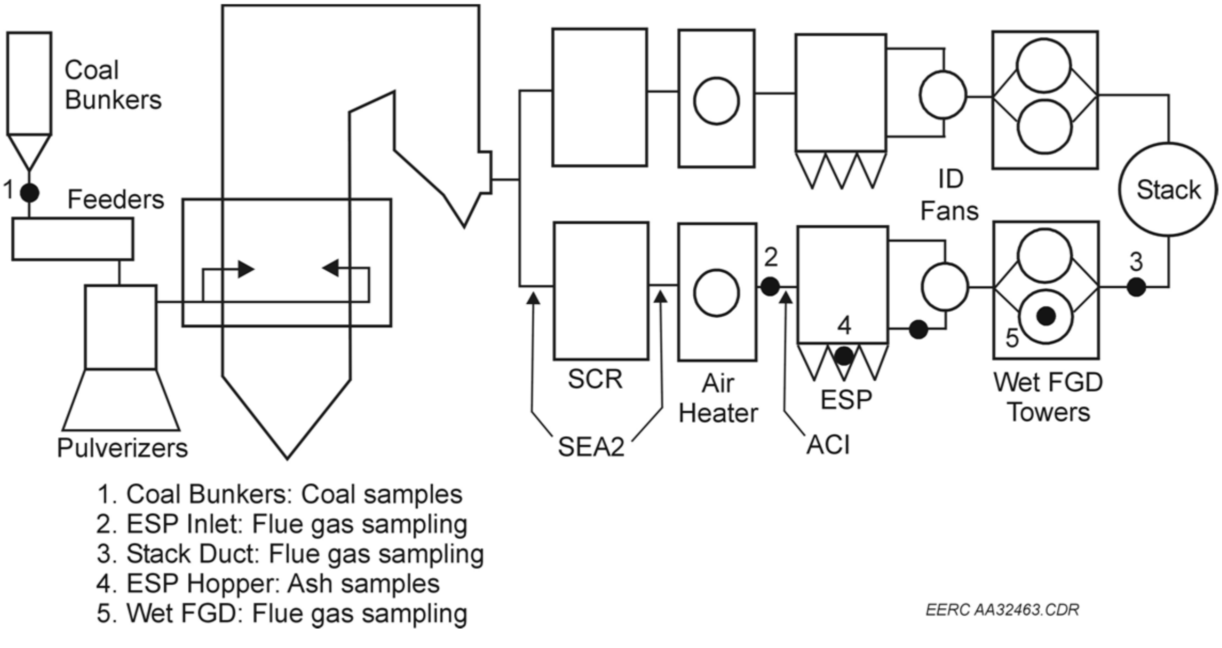


Figure 3. Schematic of MC4 showing SEA/PAC injection points and sampling locations.

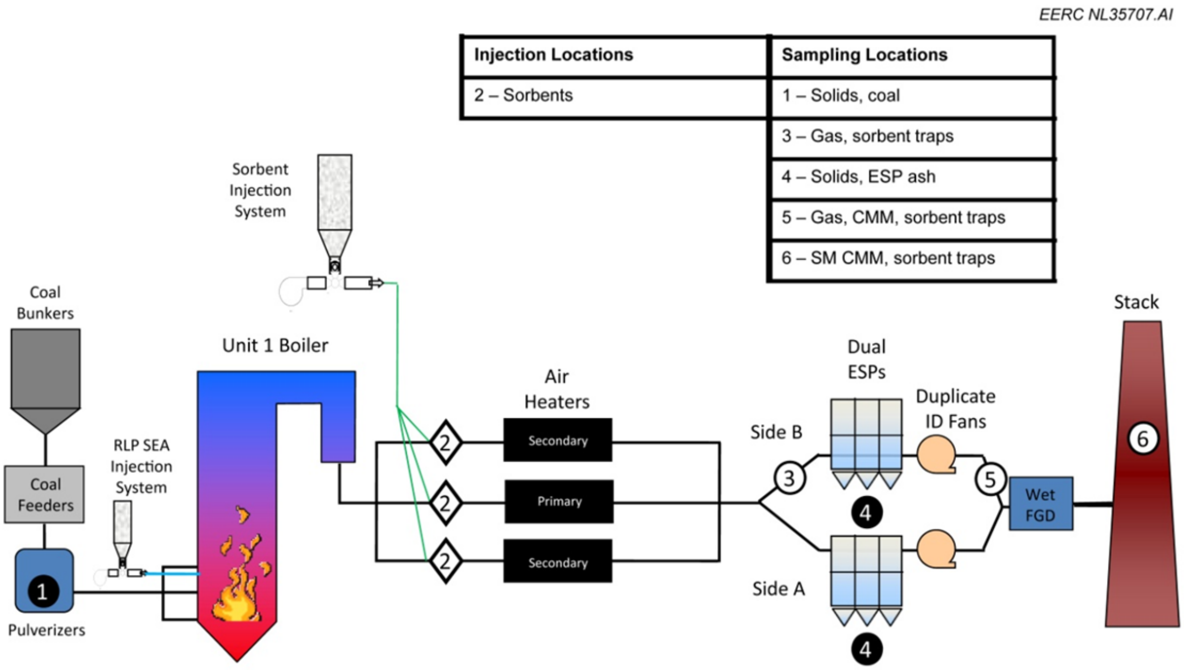


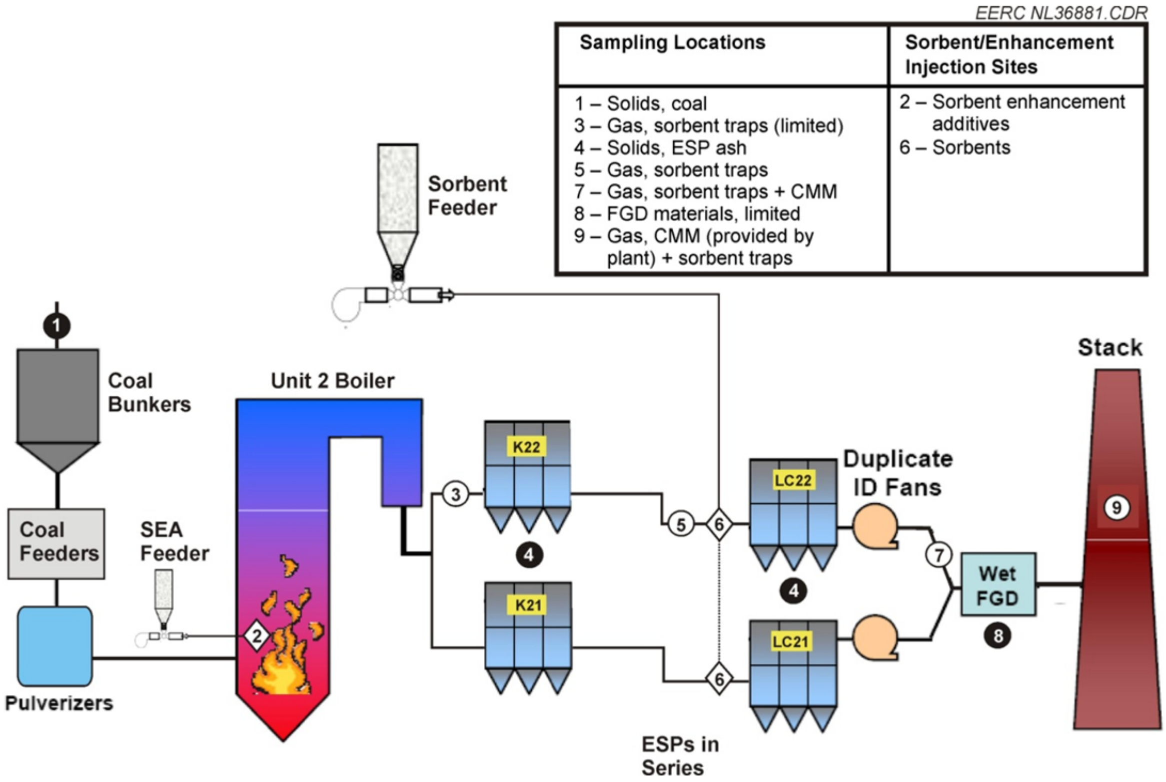
Figure 4. SM1 schematic showing injection and sampling locations.

Particulate matter is controlled on each unit by four cold-side ESPs—two parallel sets of two ESPs in series. Sulfur emissions are controlled on each unit by a scrubber. A schematic of Unit 2 that shows sampling and injection locations is presented in Figure 5.

In order to determine the mercury removal across each air pollution control device (APCD), sampling was conducted at four locations, including the Koppers inlet, Lodge inlet, induced-draft (ID) fan outlet, and stack. All of the sampling was conducted on the south side of the test unit rather than both sides of the unit in order to reduce project costs. STs were collected at each sampling location, and CMMs were installed at the Lodge inlet, ID fan outlet, and stack locations. EPA Method 26a (M26a) and M29 sampling was conducted at both the Lodge inlet and stack-sampling locations.

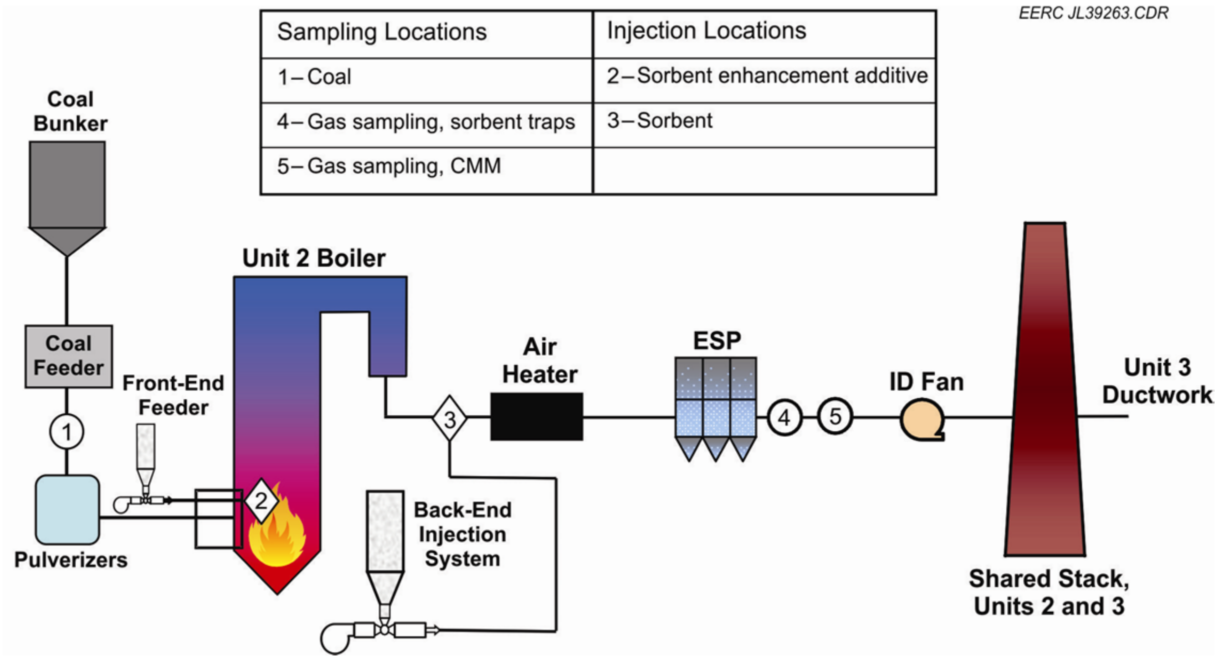
Hoot Lake Unit 2 (HL2)

Otter Tail Power's HL2 located near Fergus Falls, Minnesota, is a 54-MW tangentially fired boiler fueled by Spring Creek subbituminous coal. PM is controlled by a cold-side ESP. There are no SO_x or NO_x control systems. A schematic that shows sampling and injection locations is presented in Figure 6. The sampling location for the required ICR was located downstream of the ESP and composed of a vertical row of six ports. These ports have been verified by Otter Tail Power to meet EPA Method 1 of Appendix A of Part 60 criteria based on a prior alternative test site evaluation conducted in accordance with EPA Method 1 Section 2.5 of Appendix A of Part 60. A single port, located halfway up the duct height and approximately 5 feet downstream of the vertical ports, served as the location for the hydrocarbon sampling and the mercury continuous emission monitor (CEM).



Sampling Locations	Sorbent/Enhancement Injection Sites
1 – Solids, coal 3 – Gas, sorbent traps (limited) 4 – Solids, ESP ash 5 – Gas, sorbent traps 7 – Gas, sorbent traps + CMM 8 – FGD materials, limited 9 – Gas, CMM (provided by plant) + sorbent traps	2 – Sorbent enhancement additives 6 – Sorbents

Figure 5. Schematic of Cent2.



Sampling Locations	Injection Locations
1– Coal	2– Sorbent enhancement additive
4– Gas sampling, sorbent traps	3– Sorbent
5– Gas sampling, CMM	

Figure 6. Schematic of HL2 showing injection and sampling locations.

Sampling Methods

A list of the sampling methods can be found below in Table 4. Site-specific test methods can be found in the site report in Appendices A–D. A more detailed discussion on the mercury sampling methods and solids collection follows.

Mercury Sampling

The OH method is a technique used for the measurement of particle-bound, oxidized, elemental, and total mercury in stationary-source flue gases according to standard procedures prescribed by ASTM International (ASTM) (17). It provides data that can be used more generally for dispersion modeling, deposition evaluation, human health and environmental impact assessments, emission reporting, and compliance determinations. Particle-bound, oxidized, and elemental mercury measurements before and after control devices may be necessary for optimizing and evaluating the mercury removal efficiency of emission control technologies. As a validation of the accuracy of the method, the error tolerances in sample measurements were required to be <10% of sample value or 10 times the detection limit of equipment, < 25% of sample value for field blanks, <15% of true value for field and laboratory spikes, <10% for precision; all measurements were also required to be 100% complete in order to be considered.

To ensure the accuracy of the measurements, one field blank and one field spike were collected at each sample location per test condition and evaluated during the initial baseline and parametric testing. Following this period, OH method sampling was also done during the long-term testing. Field blanks and spikes were analyzed at each sampling location for each sampling

Table 4. Sampling Methods

HAP	Method
PM/PM Fines/Condensibles and Moisture	EPA OTM[1] 27/28
Dioxins/Furans	EPA Method 23
THC	EPA Method 25A
HCl/HF/HCN	EPA Method 26A
Multimetals	EPA Method 29
Mercury	EPA Method 30B Ontario Hydro CMM
Formaldehyde	RCRA[2] Method 0011
VOC – Speciated	EPA Method 0031
Semi-VOC – Speciated	EPA Method 0010
Cr^{6+}	RCRA Method 0061
Speciated Hg	ASTM Method D6784-02
Methane	EPA Method 18

[1] Other test method.

[2] Resource Conservation and Recovery Act.

period. The field blanks and spikes consisted of sample trains that were assembled and taken to the same location as a test sample, leak-checked, and recovered. If the field blanks did not meet the validation criteria, the data were flagged, and corrective actions were taken to determine the source of the contamination, which was possible because the analyses of blanks and field spikes were performed on-site.

CMMs were also used at each unit. The EERC provided either PS Analytical Sir Galahad or Tekran Model 2537A gold amalgamation cold-vapor atomic fluorescence spectroscopy (CVAFS)-based Hg vapor analyzers or a Thermo Scientific Mercury Freedom System^{TM}. With the two CVAF amalgamation systems, the sample gas is pulled through a stack- or duct-mounted, high-flow-rate inertial probe to minimize mercury measurement artifacts due to filtering. The probe control system allows for mercury spiking and autodilution, as well as automating the processes. Since CVAFS systems can only measure Hg^0, the sample gas requires conditioning (either a wet or dry method) to reduce oxidized mercury to Hg^0. A wet conversion system injects solutions into two separate sample flow paths, one to continuously reduce Hg^{2+} to Hg^0, resulting in a total gas-phase Hg sample, and the other to continuously scrub out Hg^{2+}, resulting in an Hg^0 sample. In a hot conversion system, the sample is first diluted and transported through a heated line to a conditioning module. The diluted sample is split into two streams. In the first stream, a thermal conditioner unit reduces all of the mercury forms present in the sample to elemental mercury. Recombination is avoided by the quantitative removal of HCl and other gases by a patented thermal conditioner/scrubber system. The second pathway removes ionic (water-soluble) mercury, leaving only the elemental mercury to pass through to the converter. This stream is then subjected to additional conditioning to remove acid gases and excess humidity from the sample. The CVAF instruments trap the Hg vapor from the conditioned sample onto a cartridge containing an ultrapure gold sorbent. The amalgamated Hg is then thermally desorbed and detected using atomic fluorescence. For both systems, ionic mercury is determined by difference.

The third EERC CMM system was a Thermo Scientific Mercury Freedom System^{TM}, which consists of a mercury analyzer, mercury calibrator, zero air supply, stack probe and inertial filter, converter, and probe control system. The mercury analyzer is a CVAFS design that provides continuous sample measurement, with no additional gases or preconcentration required. The extraction probe uses an inertial filter to separate a particulate from the gas-phase sample, minimizing reactions of mercury and other species with fly ash. All components that are exposed to sample gas are glass-coated to prevent reactions with mercury. The probe incorporates a dilution assembly and calibration gas that can be introduced either upstream or downstream of the inertial filter. A high-temperature module converts all vapor-phase species of mercury to Hg^0 for analysis. The Hg^0 calibrator is available to provide output range from 0.1 to 300 $\mu g/m^3$.

In addition to having qualified personnel to operate the CMMs for this project, the EERC followed the quality assurance/quality control (QA/QC) guidelines in Part 75, including daily calibrations. Normally, calibration is done by first sampling zero gas (air that has passed through a carbon trap), followed by injecting an exact amount of primary standard mercury vapor into the instrument. These procedures are done four times to determine the type of scatter. In addition, the internal EERC QA/QC standard is that $R^2 = 0.999$. If this standard is not met, additional calibration is completed, or more substantial maintenance of the instrument is done, which includes cleaning all lines, checking filters, etc.

Sorbent Traps

An ST method (similar to EPA Method 30B) was used in some instances to evaluate the comparative accuracy of the CMM results. The ST samples were collected with single, two-stage traps and were recovered and analyzed for mercury on-site in the EERC mobile laboratory; mercury analysis was performed using an OhioLumex mercury analyzer that is based on a thermal decomposition procedure validated by EPA followed by detection using atomic absorption spectroscopy (AAS).

The QA/QC program for analyzing the STs consisted of an initial analysis of blanks, calibration, and check standards followed by periodic checks on performance. Detailed performance records are maintained that define the quality of the data generated. The EERC chemist who performed the analysis was well trained and understands the procedures for using the OhioLumex both in the laboratory and in the field. The following outlines the calibration standards and QA/QC procedures that were followed:

- Calibration standards were prepared from National Institute of Standards and Technology (NIST)-traceable standards to span the range of sample values; the generated calibration curve was required to have an r^2 value greater than 0.99. If these requirements were not met, then the instrument was recalibrated with remade standards as necessary.

- A QC standard was made from a NIST-traceable standard from a different lot than the calibration standards and analyzed to compare to the calibration curve. This standard was required to be within ±10% of its expected value. If it was not, then either the QC standard was remade and analyzed again, or the instrument calibration was rechecked. It should be noted that, for this project, all QC standards fell within the ±10% specification.

- Analyzer calibrations are usually very stable and may be used for several days; the EERC either made or verified the calibration curve each day. QC checks at the high and low calibration points on the curve were done a minimum of twice a day (once after generating/verifying the calibration curve and once near the end of the day).

- A QA check at a concentration close to that being analyzed was made for every ten samples or twice a day, whichever was greater. If these values were within ±10% of the known standard, the calibration was still valid.

- If a calibration had to be repeated after the samples were analyzed, the data for all the samples analyzed since the last valid calibration were recalculated, based on the new calibration curve. Because the samples had been completely desorbed, it was not possible to run them again; therefore, a recalculation was done using computational processes based on the manufacturer's instructions for calculation of data. It should be noted that, for this project, all check standards fell within the ±10% specification.

- All documentation was recorded in project notebooks and/or on the computer. Data records stored on a computer were maintained and backed up. Following testing, all data sheets and log books were initialed by the person completing the analysis and reviewed for completeness and accuracy. Any changes or corrections that needed to be made were initialed, dated, and noted.

Solids and Liquids Sampling

Solids and various liquids/slurries from the process streams were collected as part of the sampling at each unit. The types of samples collected at each unit are presented in Table 5. To evaluate Hg input to the system, coal samples were collected at a minimum of once a day and in some cases once during each wet-chemistry sampling period. Either crushed or pulverized samples were collected depending on the plant sample collection protocol. Ash was collected from the particulate control device hopper. Again, the minimum was a daily sample. More samples were typically collected during parametric testing that involved changing PAC or SEA injection rates. FGD samples were collected once a day. A summary of the analysis performed on the samples collected at each unit is presented in Table 6. A full description of the samples collected and detailed analysis for each unit can be found in Appendices A–D.

Trace Metal and Particulate Sampling

In addition to the mercury data, select EPA sampling methods were also carried out at Centralia in order to assess balance-of-plant effects because of sorbent injection for mercury removal. EPA measurement of halogens using M26a sampling was conducted during baseline, DARCO Hg-LH, and SF10–SB24 ET1 test periods. EPA M29 sampling for 16 other trace elements (antimony, arsenic, barium, beryllium, cadmium, chromium, cobalt, copper, lead, manganese, nickel, phosphorus, selenium, silver, thallium, and zinc) was conducted during baseline conditions and sorbent injection. EPA M5 sampling during baseline and SF10–SB24 ET1 test conditions was completed to evaluate the effect of sorbent injection on particulate emissions as a result of sorbent injection.

ICR Sampling

At Hoot Lake, the sampling location for the required ICR was located downstream of the ESP and composed of a vertical row of six ports. A summary of the ICR sampling methods is presented in Table 7 All samples were collected in the Unit 2 duct. For detailed information on the ICR test matrix, see Appendix D. The sampling methods were conducted following guidelines set forth in Title 40 of the Code of Federal Regulations Part 60 Appendix A (40 CFR Part 60) and listed on EPA's Technology Transfer Network Emissions Measurement Center Web site (www.epa.gov/tnn/emc) and EPA's online resource for SW-846 (Test Methods for Evaluating Solid Waste, Physical/Chemical Methods: www.epa.gov/osw/hazard/testmethods/sw846/online/index.htm).

Table 5. Solids and Liquids Sample Collection

Material	HAW5	MC4	SM1	CENT2	HL2
Coal	X	X	X	X	X
PCD* Hopper Ash	X	X	X	X	X
Limestone	X	X			
Reagent Feed				X	
FGD Slurry	X	X		X	
Gypsum	X	X		X	

*Particulate collection device.

Table 6. Sample Analysis

Sample		HAW5	MC4	SM1	CENT2	HL2
Coal						
	Proximate/Ultimate	X	X	X	X	X
	Btu	X	X	X	X	NA
	Hg	X	X	X	X	X
	Cl	X	X	X	X	NA
	Br	NA*	NA	X	NA	NA
	As	NA	NA	X	NA	NA
	Se	NA	NA	X	NA	NA
Ash						
	LOI	X	X	NA	NA	NA
	Hg	X	X	X	X	X
	Cl	NA	NA	NA	X	NA
	Br	NA	NA	NA	X	NA
Limestone						
	Hg	X	X	NA	NA	NA
Reagent Feed						
Liquid	Hg	NA	NA	NA	X	NA
Solid	Hg	NA	NA	NA	X	NA
FGD Slurry						
Liquid	Hg	X	X	NA	X	NA
Solid	Hg	X	NA	NA	X	NA
Gypsum						
	Hg	X	X	NA	X	NA

* Not analyzed.

CCP Mineralogical Analysis Methods

A limited number of CCPs were analyzed by scanning electron microscopy (SEM). The samples were prepared into paste mixtures, subjected to various leaching methods, or analyzed on an as-received basis.

Table 7. Test Matrix for ICR Sampling at HL2

EPA Sampling Method	Analyte	Analytical Method
3B	O_2 and CO_2	Orsat
4	H_2O	Gravimetric
6C or CEM	SO_2	CEM
7E or CEM	NO_x	CEM
10	CO	CEM
25A	THC	GC–FID[1]
0010	Speciated SVOCs[2]	GC–MS[3]
0031	Speciated VOCs	GC–MS
0011	Formaldehyde	GC–MS
18	CH_4	GC/FID
23	Dioxins/furans	GC–MS
26A	Halogens (HCl and HF)	IC[4]
26A and OTM-033	HCN	IC
OTM 27	$PM_{2.5}$	Gravimetric
OTM 28	Condensable PM	Gravimetric/extraction
29	Metal HAPs (including Hg)	ICP–MS[5]

[1] Gas chromatography–flame ionization detection.
[2] Semivolatile organic compound.
[3] Gas chromatography–mass spectroscopy.
[4] Ion chromatography.
[5] Inductively coupled plasma–mass spectrometry.

Preparation of Paste Mixtures

The preparation and subsequent curing of the fly ash–cement pastes, in mortar blocks specifically designed for SEM samples, was performed according to standard test method ASTM C311 “Sampling and Testing Fly Ash or Natural Pozzolans for Use in Portland-Cement Concrete.” The mixture consisted of cement, absorbent, and graded sand. The mass ratio of the cement and fly ash was 4:1. The mass ratio of sand to powder was 2.75:1, with a water content of approximately 13%. After mixing the materials according to the specified C311 procedure, the molded blocks were placing into a curing chamber and cured overnight. The following day, the sample blocks were removed from their molds and cut with a diamond saw to reveal a fresh surface. This surface was polished and carbon-coated for analysis by SEM.

The cured cement paste blocks were analyzed in a variable-pressure SEM. The variable-pressure SEM is a JEOL 5800 LV (low vacuum) with an aperture that is very small and a large vacuum pump that allows the column to be in hard vacuum and the sample chamber to have a small amount of pressure. This reduced the outgassing of the moisture in the paste samples allowing for imaging and analysis in the SEM. The analytical system used is the Princeton Gamma Tech Spirit system, and the detector is a NORAN Instruments lithium-drifted silicon (SiLi) Pioneer detector.

Leaching Studies

Leaching was conducted using the synthetic groundwater leaching procedure (SGLP), which is an 18-hour test, and long-term leaching (LTL) on one set of Fort Union lignite CCPs. The SGLP batch-leaching procedure follows many of the conditions of ASTM D3987. The test utilizes a 20:1 liquid-to-solid ratio, end-over-end agitation at approximately 30 rpm, and an 18-hour equilibration time and usually employs a leaching solution consisting of water from the disposal or utilization site, water that has been prepared in the lab similar to water likely to contact the CCP, or distilled deionized water (18). Distilled deionized water was used as the leaching solution in this effort. The LTL component generally consists of 30- and 60-day equilibration periods to determine a trend of leaching through the concentration evolution of individual parameters. A 30-day equilibration period was used for this study to determine if a difference in ettringite formation existed between the samples in question.

A standard subbituminous CCP sample was also leached utilizing two of the numerous leaching conditions under the "Integrated Framework for Evaluating Leaching in Waste Management and Utilization of Secondary Materials" (19) methodology, which is recommended by the EPA. The conditions were chosen from the Tier 2 procedure, which consists of separate leachate samples at eleven target pH levels of pH 2–12 at a liquid-to-solid ratio of 10:1 using distilled, deionized water plus a calculated amount of 2 N nitric acid (HNO_3) or 1 N potassium hydroxide (KOH) from a titration pretest. For this project, the CCP sample was leached at the natural pH (without acid or base addition) and with an addition of 1 N KOH as determined previously in the titration pretest for a target pH level of 12. The CCP was rotated over a 24-hour period with end-over-end agitation at approximately 30 rpm for each condition. A long-term component using a 30-day equilibration period was added for each of the conditions.

For the long-term component of the leaching procedures, multiple bottles were set up and analyzed at the 30-day interval. For all leaching procedures, the solids were filtered from the leaching solution through coarse filter paper. The leached and filtered CCP samples were oven-dried at <36°C in preparation for mineralogical analyses.

The oven-dried and two as-received CCP samples were analyzed in a JEOL 5800 SEM newly equipped with an Oxford Instruments INCA Energy EDS system. This system is an energy-dispersive spectroscopy (EDS) system that utilizes a silicon drift detector (SDD) for x-ray counts. SDDs are electronically cooled and do not rely on liquid nitrogen for that purpose and are capable of much higher count rates than SiLi detectors.

RESULTS AND DISCUSSION

Parametric testing of sorbent, SEA, and sorbent with SEA injection was performed at each unit to identify the best technology and optimum conditions that could achieve the targeted mercury removal rates. Mercury removal efficiencies are either based on the difference between the mercury measured in the coal and the mercury measured in the stack or the difference between the mercury measured in the stack at baseline conditions and during injection. A period of steady-state plant operation during which baseline mercury concentrations were established preceded each injection period. The baseline period is also used to determine if there are any periodic changes associated with normal plant operations. All results were corrected to 3% O_2 for equal comparison. A brief discussion of the technologies that achieved the target removal rates at each unit is presented below.

Hawthorn Unit 5

A summary of all of the technologies evaluated at HAW5 is presented in Table 8 Two technologies were identified that were able to achieve >90% total Hg removal from coal mercury levels. The highest removal (94%) was achieved with PAC (DARCO Hg-LH) injected at a rate of 2 lb/Macf with SEA1 injection at an equivalent Cl_2 rate of 500 ppm. Injection of this PAC alone at a rate of 3.3 lb/Macf averaged only 47.6% Hg capture and SEA2 alone at an equivalent

Table 8. Comparison of the Performances of the Various Additives Tested at HAW5

	Percent Total Hg Removal	
Additive	From Baseline	From Coal
Cl_2 600 ppm	66.9	72.7
Cl_2 800 ppm	75.9	80.1
Cl_2 1000 ppm	72.0	76.9
Cl_2 1200 ppm	75.4	79.7
DARCO Hg 1 lb/Macf	39.8	59.0
DARCO Hg 2.75 lb/Macf	60.9	69.5
DARCO Hg 3.3 lb/Macf	32.9	47.6
DARCO Hg 2 lb/Macf and Cl_2 250 ppm	85.7	88.2
DARCO Hg 2 lb/Macf and Cl_2 500 ppm	**92.7**	**94.0**
DARCO Hg 3.3 lb/ Macf and Cl_2 800 ppm	51.8	62.4
DARCO Hg 3.3 lb/ Macf and Cl_2 1000 ppm	58.0	67.2
DARCO Hg 3.6 lb/ Macf and Cl_2 1000 ppm	70.2	76.7
DARCO Hg 3 lb/Macf and Cl_2 1200 ppm	86.3	89.3
DARCO Hg 3.6 lb/ Macf and Cl_2 1200 ppm	81.4	85.4
DARCO Hg 4lb/Macf and Cl_2 1200 ppm	85.0	88.3
DARCO Hg 2.75 lb/Macf and SEA2	72.2	78.3
DARCO Hg 3.3 lb/ Macf and SEA2	69.0	75.8
DARCO Hg 1 lb/Macf and SEA2 2 lb/hr	51.6	67.0
DARCO Hg 1 lb/Macf and SEA2 6 lb/hr	48.5	64.9
DARCO Hg 3 lb/Macf and SEA2 18 lb/hr	79.2	85.8
DARCO Hg-LH 1 lb/Macf	58.9	72.6
DARCO Hg-LH 2 lb/Macf	83.7	89.1
DARCO Hg-LH 3 lb/Macf	**89.7**	**93.1**
DARCO Hg 1 lb/Macf	60.5	73.7
DARCO Hg 2 lb/Macf	72.0	81.3
DARCO Hg 3 lb/Macf	62.3	74.9
DARCO Hg 2 lb/Macf with SEA2 via HETD skid	69.1	79.4

injection of 600 ppm Cl_2 achieved 72.7%. Injection of Norit Americas DARCO Hg-LH carbon at a rate of 3 lb/Macf also achieved 93.1% mercury capture and just under 90% at a rate of 2 lb/Macf. The SEA2 additive achieved a maximum removal of 85.8% only when injected at a high rate and with a high rate of PAC injection. A complete discussion of the results from testing at Hawthorn is given in Appendix A.

Mill Creek Unit 4

The primary technologies tested at MC4 included SEA2-T2, PAC, and B&W scrubber additives and various combinations of these techniques. A summary of the results from the parametric testing is presented in Table 9. It is clear from the results that PAC injection had a possible negative impact on baseline Hg removal and did not help when used in conjunction with the other additives. The B&W additive alone is the only technology to achieve the target of >90% mercury capture. Based on these results, a decision was reached by the project team, including DOE, to use the B&W wet FGD additive, which attained >90% removal at an add rate of 80 g/hr, for the long-term demonstration study. A complete discussion of the results from testing at Hawthorn is given in Appendix A.

At MC4, long-term injection tests using the B&W reemission additive were conducted continuously for a period of about 1 month. The B&W reemission additive was injected at a nominal rate of 80 g/hr as predetermined from the results of parametric tests. During the long-term test period, daily coal samples were analyzed for Hg, Cl_2, proximate and ultimate

Table 9. Summary of the Results of Parametric Tests at MC4

Test Condition	Coal–FGD Hg Removal, %	ESP–FGD Hg Removal, %
Baseline	78.0	86.7
PAC 0.5 lb/Macf	60.5	67.6
PAC 1.0 lb/Macf	67.2	72.3
PAC 1.5 lb/Macf	75.9	82.7
PAC 1.0 lb/Macf	76.1	71.8
B&W 30 g/hr	83.5	87.5
B&W 45 g/hr	85.7	**91.3**
B&W 80 g/hr	**90.8**	**–**
PAC 1.0 lb/Macf and B&W 30 g/hr	68.1	87.9
PAC 1.0 lb/Macf and B&W 60 g/hr	85.3	–
PAC 1.0 lb/Macf and B&W 80 g/hr	89.3	–
SEA2 2.5 lb/hr	73.4	71.1
SEA2 5 lb/hr – incomplete	74.1	71.0
PAC 1.0 lb/Macf and SEA2 2.5 lb/hr	73.1	57.6
PAC 1.0 lb/Macf and SEA2 5 lb/hr	71.9	65.4
PAC 1.0 lb/Macf and SEA2 5 lb/hr	78.2	59.0

properties, and heating value. The mercury concentration at the ESP outlet and wet FGD outlet was monitored on a continuous basis using the CMMs. In Figure 7, hourly averaged elemental and total Hg values are plotted for both the ESP outlet (middle plot) and the FGD outlet (bottom plot) CMMs. The calculated ESP-outlet to FGD-outlet Hg removal values is also included in Figure 7 (top plot). Note that data points corresponding to periods when additive injection was interrupted due to maintenance have been removed. Figure 8 also shows the overall performance of the additive over the entire period and, in particular, points to some dates when the additive was interrupted. Although there are still a few spikes that indicate less than 90% removal, there are large periods of time where the efficiency is consistently above 95%. An overall average Hg removal efficiency of 91.8% was attained during the 1-month test period.

A mercury mass balance was calculated across MC4 at the end of the long-term test in a similar manner as with the baseline mass balance. The amount of mercury emitted from the stack during the long term B&W reemission additive injection testing (0.00213 lb/hr) was significantly lower than emitted during baseline conditions (0.00787 lb/hr). This resulted in an improved coal-to-stack Hg removal of 94%. The long-term Hg mass balance closure was 75.8%, which is lower than during baseline tests. During long-term testing, a clear drop in FGD flue gas outlet Hg was detected, but an expected concomitant rise in captured Hg leaving the FGD (e.g., in the gypsum, cake wash outlet, or chlorides blowdown) was not observed. Some of the discrepancy may be a result of the variability observed with the mercury content of the slurry samples. During the long-term test, a change was made in the sample collection protocol, where the samples were separated into solid and liquid fractions soon after collection. Figure 9 is a plot of the mercury concentration in the liquid portion of the three FGD thickener streams. It is apparent that switching to field filtering had a dramatic effect on the amount of mercury detected in the liquid phase and that there was a significant amount of variation in these readings.

The field-filtering procedure was implemented as a protocol to satisfy the requirements of the related trace element sampling that also occurred during the long-term test. Prior to the implementation of this protocol, unseparated slurry samples were returned to the EERC and allowed to settle by gravity into liquid and solid fractions. For the field-filtering procedure, the slurry samples were separated with a vacuum filter soon after the samples were collected. Separate solid and liquid samples were then sent back to the EERC for analysis. Figure 9 indicates that the results from the gravity-separated samples were much lower in Hg and were more consistent. Conversely, the field-filtered samples have higher mercury contents in the liquid fractions and are much more erratic. It appears that the field filtering left some mercury in the liquid portion that would normally settle out with time during gravity separation.

San Miguel Unit 1

At SM1, because of the limited number of coal samples collected and the high degree of variability of the mercury in the coal, mercury percent removals were only calculated based on inlet flue gas mercury concentrations and stack measurements. The mercury concentrations in the system were characterized by a combination of OH method, ST, and CMM measurements. During the course of the baseline, parametric, and extended tests, the plant stack

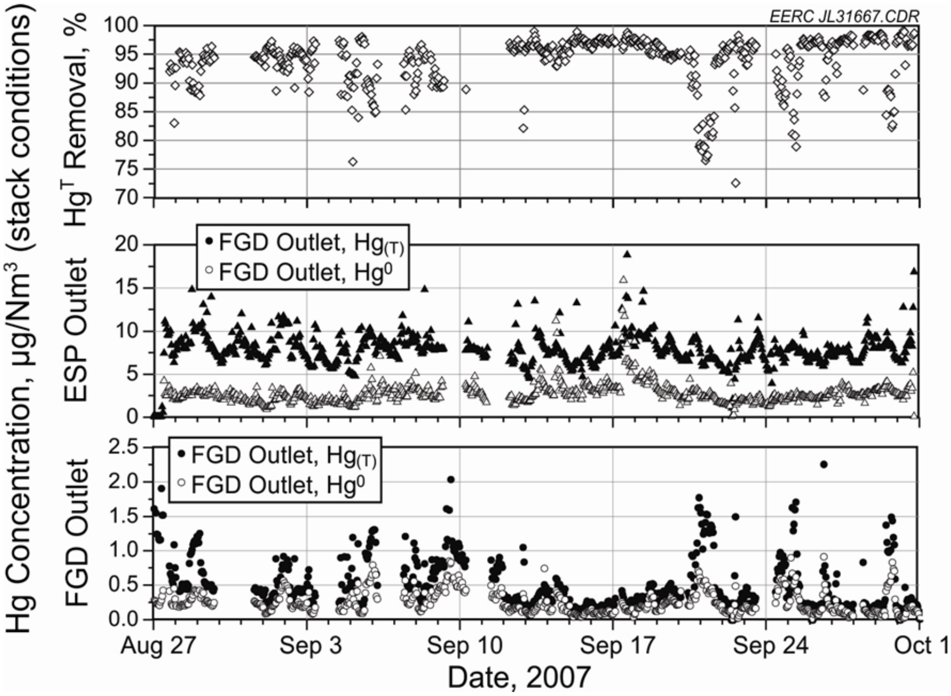


Figure 7. Hourly average CMM-based mercury removal (top) and CMM data at the ESP (middle) and FGD (bottom) outlets. Data points corresponding to periods when additive addition was interrupted have been removed.

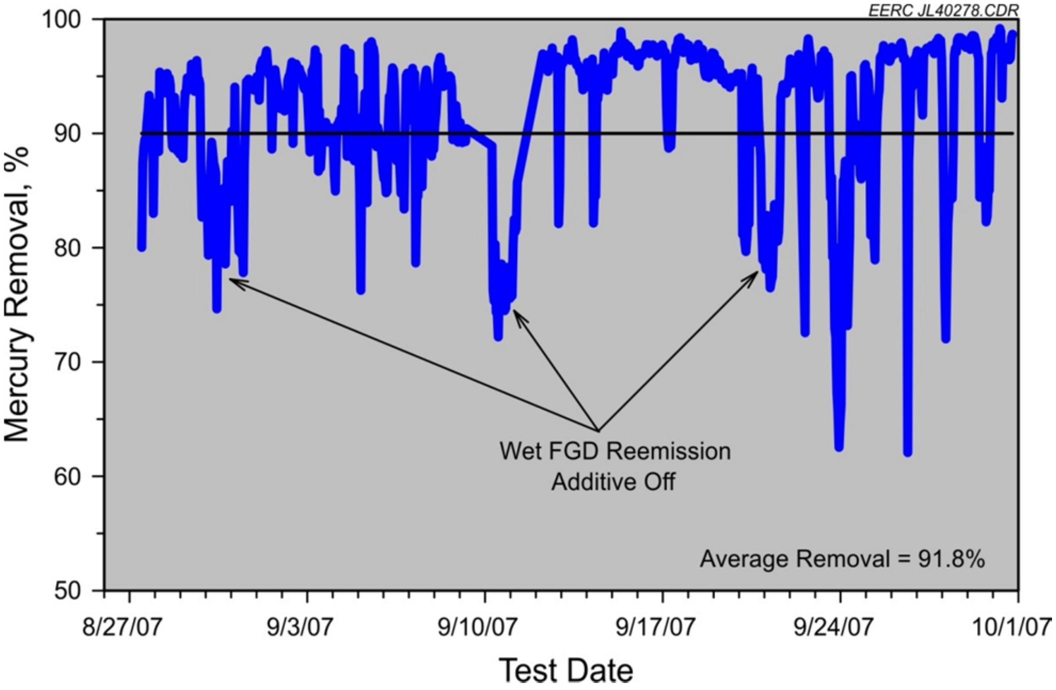


Figure 8. Plot of mercury removal efficiencies obtained at MC4 during long-term testing over a period of 1-month.

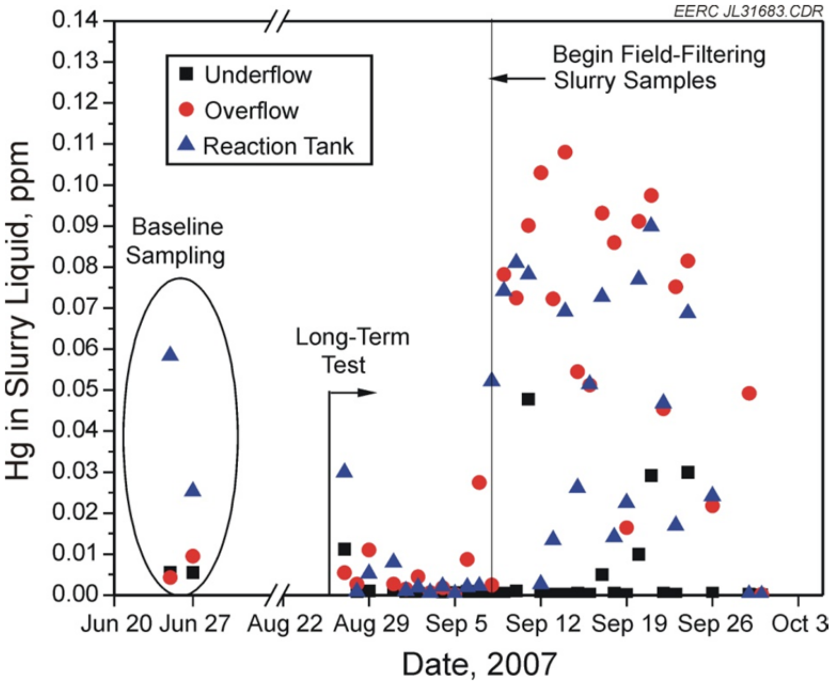


Figure 9. Mercury concentration of the liquid portions of the FGD slurry samples during baseline and long-term testing.

CMM was not functioning properly and did not provide any reliable data during the test period. The stack CMM was removed from the stack a few weeks prior to the EERC coming on-site so that stack repairs could be made. Numerous repairs, calibrations, and cleaning procedures were performed with no success. Since the stack CMM was not functioning properly, more STs were collected in order to obtain stack data.

The baseline testing showed an average increase of 2.88 μg/dNm^3 at 3% O_2 (15.1%) in elemental mercury across the scrubber, indicating that scrubber reemission is occurring. Each parametric test was performed long enough for the scrubber inlet CMM to reach an apparent steady state, typically for durations of 0.5 to 4 hours. Injections were started at a relatively low rate and then gradually increased to minimize potential memory effects from the higher injection rates. After a parametric test was completed, the next test was not started until the CMM concentrations returned to the values obtained during the baseline test period. During many of the parametric tests, simultaneous ST measurements were made at the scrubber inlet and stack locations to verify the CMM results and obtain data from a different technique than the CMM. Two sets of OH method measurements were also collected during the parametric test period in order to obtain mercury speciation data.

The mercury control technologies evaluated at SM1 included four different powdered sorbents (two from Norit Americas and two from RLP Energy), one SEA from RLP Energy, and B&W's scrubber additive to prevent reemission of mercury. A summary of the highest collection efficiencies achieved with each technology is presented in Table 10. For the parametric testing,

Table 10. Summary of the Results of Parametric Tests at SM1

Test Condition	ESP–FGD Hg Removal, %
Baseline	42.4
DARCO Hg at 4.0 lb/Macf	71.5
DARCO Hg-LH at 3.5 lb/Macf	73.4
SF11 at 60 lb/hr	66.3
SB11 at 3.5 lb/Macf and SF11 at 80 lb/hr	81.7
SB26 at 3.5 lb/Macf and SF11 at 80 lb/hr	66.3
DARCO Hg-LH at 3.0 lb/Macf B&W scrubber additive at 1400 lb/hr	33.2

all sorbent materials were injected upstream of the air heater inlet, and the SEA was injected into the furnace. The maximum mercury capture efficiency measured while the DARCO Hg was injected was only 71.5% at an injection rate of 4 lb/Macf. Using the average coal mercury concentration, the maximum coal to stack removal was roughly 81%, still less than the target removal efficiency. Results were slightly better using the DARCO Hg-LH with a maximum removal efficiency of 73.4% at a lower injection rate. The two back-end sorbents supplied by RLP Energy were designated SB11 and SB26. SB11 is a carbon-based material, and SB26 is a non-carbon-based material with "concrete-compatible" characteristics. The SEA provided by RLP Energy is a non-carbon-based material called SF11.

The first set of parametric tests involved the injection of the SF11 SEA without back-end sorbent injection to evaluate the effectiveness of adding the SEA alone on mercury capture by the fly ash. There was only a slight increase in mercury removal across the ESP as SF11 rates were increased. At the highest SF11 injection rate of 60 lb/hr, the mercury removal was only 66.3%. The speciation data show that SF11 oxidized the mercury but had very little effect on the ability of the fly ash to capture mercury. The oxidized mercury instead traveled through the ESP and was subsequently removed in the scrubber.

SF11 was also introduced in conjunction with SB11 to evaluate the synergistic effect between the two materials. During the parametric tests, both the SF11 and SB11 injection rates were parametrically increased at the same time. Mercury capture increased with increasing rates of injection for the SF11 and SB11. The maximum removal efficiency of 81.7% was measured at injection rates of 80 lb/hr of SF11 and 3.5 lb/Macf of SB11.

The concrete-compatible sorbent, SB26, was evaluated in an extended test with SF11 to determine its mercury removal effectiveness at SMEC. The extended test used constant SF11 and SB26 injection rates of 80 lb/hr and 3.5 lb/Macf. The extended test rates were held consistent over a 9-hour period. The maximum removal using this combination was 66.3%. This shows that this technology combination does not offer much improvement over the SF11 additive alone.

In an attempt to reduce or eliminate scrubber reemission at SMEC, a B&W scrubber additive was added to two of the scrubber absorber columns. The scrubber additive rates were parametrically increased from 600 to 1400 lb/hr while DARCO Hg-LH was injected at a constant rate of 3.0 lb/Macf. Scrubber inlet CMM data, stack ST data, scrubber inlet OH method data, and stack OH method data were all used to determine if reemission was still occurring and if the scrubber additive had any impact on scrubber reemission. All of the data show the scrubber inlet concentration was constant throughout the testing, and the outlet data show that the mercury removal remained consistent throughout all of the scrubber additive rates tested. When the scrubber inlet Hg^0 data (CMM and OH method) are compared to the stack $Hg_{(T)}$ data (ST and OH method), it is apparent that reemission is still occurring at each scrubber additive injection rate because the scrubber inlet Hg^0 data are 2–4 $\mu g/dNm^3$ at 3% O_2 lower than the stack $Hg_{(T)}$ data. This amount of reemission is consistent with the parametric tests where the scrubber additive was not being tested and indicates that the scrubber additive demonstrated little to no impact on mercury reemission.

Centralia Unit 2

Parametric Testing

Following the baseline test period, parametric tests were performed to determine the sorbent injection rates necessary to obtain ≥ 80% mercury removal. Each parametric test was performed long enough for the CMMs to reach an apparent steady state, typically for durations of 0.5 to 4 hr. One technology was tested a day to allow the unit to recover overnight and return to baseline conditions. A variety of carbon and non-carbon-based sorbents were evaluated during this test program for mercury control. The non-carbon-based sorbents were tested because of their potential concrete-compatible characteristics. A summary of the maximum mercury removal rates for each technology is presented in Table 11. For complete results from each parametric test, see Appendix C.

Two Norit Americas sorbents, DARCO Hg-LH and DARCO Hg-CC, were parametrically tested to evaluate their mercury removal effectiveness. Figure 10 displays the percent mercury removals during the injection of DARCO Hg-LH. The mercury removals increased until a maximum stack mercury removal of 81.79% at an injection rate of 520 lb/hr. From the plot, it appears higher removal rates may have been achieved. However, higher injection rates were not economically feasible. A maximum removal rate while the DARCO Hg-CC was injected was reached, which was slightly less than the target rate of >80%.

In addition to the Norit Americas sorbents, several front- and back-end mercury removal technologies provided by RLP Energy were parametrically tested to determine their mercury removal effectiveness. Both carbon-based and non-carbon-based sorbents were tested in conjunction with an SEA, SF10. The furnace SEA is added in conjunction with the back-end sorbent to provide a synergistic effect between the two materials, which results in an increase in the amount of mercury subsequently captured in the APCDs of the test unit.

SF10 was parametrically tested by itself to determine its mercury removal effectiveness. This technology was the only one that did not achieve the target of >80% removal. However, SF10 is intended as a front-end additive to enhance the performance of back-end additives. The RLP Energy technology combinations all met or exceeded the target removal goal of >80%. The SF10–SB24 combination even exceeded 90% mercury capture.

Table 11. Summary of the Results of Parametric Tests at Cent2

Test Condition	ESP–FGD Hg Removal, %
Baseline	
DARCO Hg-LH at 3.5 lb/Macf	81.79
DARCO Hg-CC at 4.0 lb/Macf	79
SF10 at 102 lb/hr	68.0
SB24 at 3.0 lb/Macf and SF10 at 90 lb/hr	91.73
SB21 at 4.0 lb/Macf and SF10 at 90 lb/hr	88.36
SB26 at 3.0 lb/Macf and SF10 at 90 lb/hr	82.36
SB17 at 3.0 lb/Macf and SF10 at 90 lb/hr	80.82

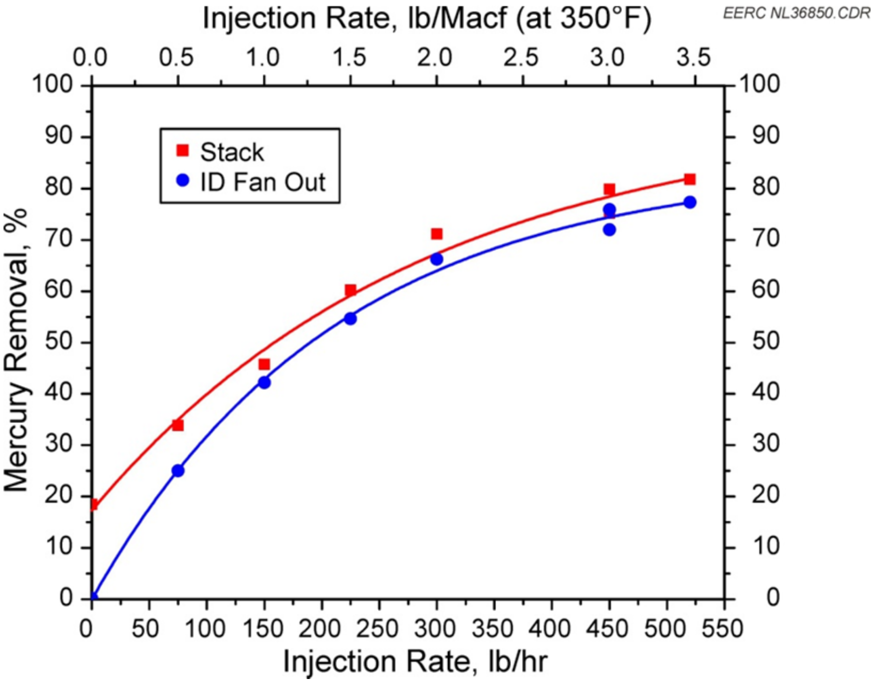


Figure 10. ID fan outlet and stack percent mercury removals as a function of DARCO Hg-LH injection rates. Injection rates are for the entire unit.

The two RLP Energy non-carbon-based sorbents, SB17 and SB26, were parametrically tested to determine their mercury removal effectiveness. Results show that the target level of >80% mercury removal could be achieved with either material without injection of a front-end SEA material.

Extended Testing

In the initial test plan, one 21-day extended test was scheduled. Based on discussions between TransAlta, the plant, and the EERC, the extended test matrix was revised. Rather than one 21-day extended test, four extended tests targeting 60%, 70%, 80%, and 90% mercury removal were scheduled. Each extended test was scheduled to last approximately 5 days in length and consist of continuous 24 hours/day sorbent injection for the duration of the test period. SF10–SB24 was the technology chosen for the extended tests because of its strong performance during the parametric test period.

The first extended test (ET1) was 5 days in duration and targeted a 60% mercury removal using SF10–SB24 at injection rates of 20 and 50 lb/hr, respectively. The average ST inlet-to-stack CMM outlet mercury removal was 72.4%.

For ET2, the SF10 and SB24 injection rates were increased to 25 and 100 lb/hr, with a target mercury removal of >70%.The average ST inlet-to-stack CMM outlet mercury removal was 87.5%, which is above the target mercury removal of >70%.

ET3 was approximately 4 days in length and utilized SF10 and SB24 injection rates of 38 and 150 lb/hr, respectively. ET3 was slightly shorter in duration because of a plugged injection hose on the south side of the unit. The average ST inlet-to-stack CMM outlet mercury removal was 90.4%, which is much higher than the target mercury removal of ≥ 80%.

The last extended test, ET4, involved injecting SF10–SB24 at high injection rates in order to determine the maximum mercury removal that is economically feasible for the unit. The test was shorter than the other extended tests and lasted for approximately a day. The SF10–SB24 injection rates tested were 60 and 225 lb/hr. The average ST inlet-to-stack CMM outlet mercury removal was 92.4%. Even at these high injection rates, an increase in mercury removal was seen when the load was decreased to approximately 475 MW for a few hours.

Table 12 presents the stack average mercury removals for each of the extended tests. The mercury removals are calculated via three methods: ST Lodge ESP inlet to stack CMM, coal to stack CMM, and ST Lodge ESP inlet to ST ID fan outlet. Both tables show that there is only a slight difference between the three different calculation methods. The tables show that there is approximately a 10% increase in mercury removal across the scrubber during the extended tests. The parametric tests indicated only about a 5% increase in mercury removal across the scrubber. This shows that the scrubber requires additional time to reach steady-state mercury removal.

Figure 11 plots the mercury removal efficiencies at the ID fan outlet and the stack for the extended test. The figure shows that the extended test data fit a smooth curve. Based on the stack mercury removal curve, 60% mercury removal can be obtained at SF10 and SB24 injection rates of 20 and 38 lb/hr, respectively. In order to obtain 70% mercury removal, the injection rates need to be increased to 22 and 54 lb/hr. Based on the stack mercury removal curve, 80% mercury removal can be obtained at SF10 and SB24 injection rates of 24 and 83 lb/hr. The extended test

Table 12. Extended Test Mercury Removals at the Stack

	SF10, lb/hr	SB24, lb/hr	ST to CMM, %	Coal to CMM, %	ST Inlet to Stack ST, %	Average, %
ET1	20	50	72.4	62.3	68.8	67.8
ET2	25	100	87.5	85.6	81.1	84.7
ET3	38	150	90.4	88.9	86.3	88.5
ET4	60	225	92.4	92.5	88.4	91.1

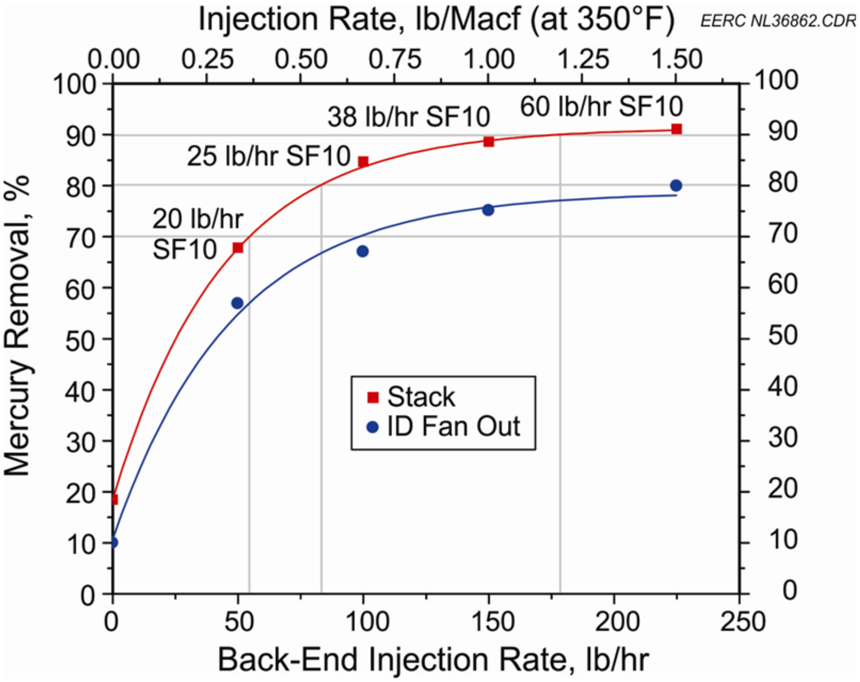


Figure 11. Summary of SF10–SB24 extended test mercury removal data. The injection rates are for the entire unit.

data show that 90% mercury removal can be achieved at injection rates of 52 and 178 lb/hr. These rates agree well with the parametric data and show that the parametric data provide useful estimates for extended tests.

Alternate SEA Testing

In addition to the parametric and extended test plan, an extra project phase was added which focused on parametric and extended testing of a near-commercial prototype alternative SEA technology (SEA2-T2). This technology has the ability to introduce the SEA at any location within the flue gas stream and/or sorbent injection line to promote mercury capture. For these tests, the alternative SEA was introduced along with the sorbent and then conveyed into the flue gas via the same splitter and injection lances previously described.

Parametric tests were performed to determine the effectiveness of the alternate SEA technology and to determine the effectiveness of different RLP Energy SEAs in conjunction with it. Each parametric test was performed long enough for the CMMs to reach an apparent steady state, typically for durations of 0.5 to 2 hours. Injections were started at relatively low rates and then systematically increased to higher injection rates in order to minimize potential memory effects from the higher injection rates. ST measurements were also periodically collected to compare the ST values to the CMM values. The results of the tests are summarized in Table 13.

One 8-hr extended test was conducted with the SC1–SB24 technology to determine the effectiveness of the technology for an extended test period. The SC1–SB24 injection rates used for this test period were 19.7 and 150 lb/hr, respectively. Figure 12 displays the CMM mercury data for the duration of the extended test along with the plant load. The CMM data show that the mercury removal at both the ID fan outlet and stack remained consistent throughout the test period. The average mercury removals at the ID fan outlet and stack were 65.98% and 70.38%, respectively. These removals are consistent with the parametric data presented in Table 13.

Comparison of Alternate SEA Technology

Figure 13 displays the alternate SEA injection results along with the other best technologies that were tested. The figure shows that the alternate SEA mercury removal results are much higher than the AC mercury removals at equivalent injection rates. The alternate SEA technology with the poorest performance had approximately a 10% higher mercury removal than the AC technologies at the same injection rates. At equivalent injection rates, the SC1–SB24 and SC3–SB24 mercury removal results are approximately 10% lower than the SF10–SB24 mercury removal results, but are 30%–35% higher than the DARCO Hg-LH and DARCO Hg-CC mercury removal results. This shows that the alternate SEA technology performs much better than treated carbons but, in its current design and state of operation, not quite as well as the SF10–SB24 technology. Based on the limited data, the alternate SEA technology shows that it is a feasible alternative to treated AC technologies, but currently does not perform as well as the best SEA–sorbent-based technologies. Further improvements on design and operation of the alternate SEA are expected to improve on these results.

Table 13. Summary of Alternative SEA Performance

SEA/Sorbent	Sea Injection Rate, lb/hr	Sorbent Injection Rate, lb/hr	Maximum Hg Capture, %
SC1–SB24	28.8	150	78.63[a]
SC3–SB24	19.3[b]	75[b]	77.4[c]
SC6–SB24	23.5	150	61.7[a]

[a] Coal-to-stack mercury capture.
[b] Injected into half of the unit.
[c] Coal-to-ID fan outlet mercury capture.

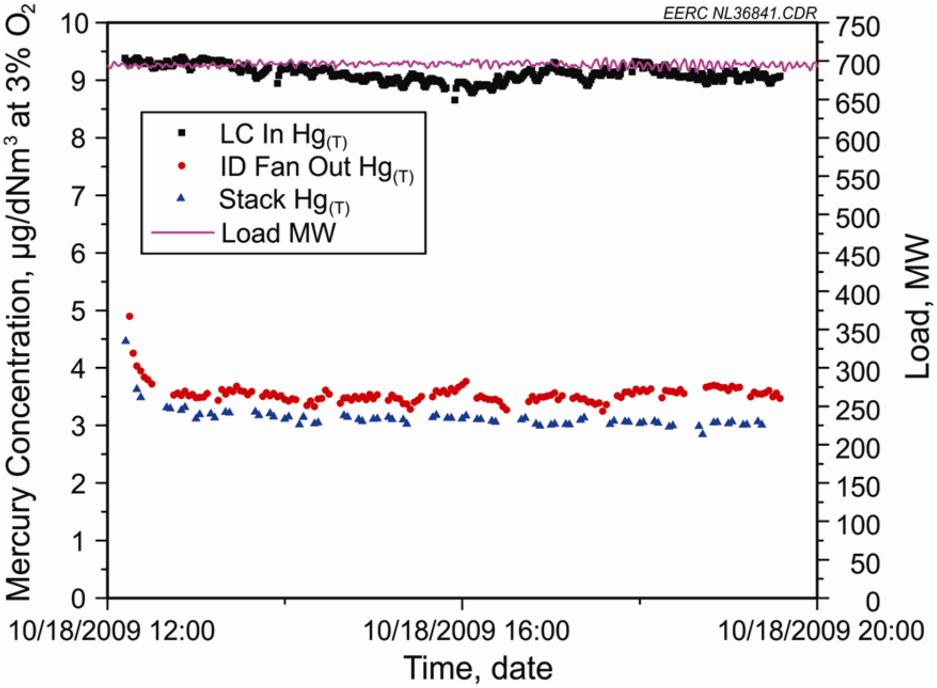


Figure 12. SC1–SB24 extended test CMM data. SC1 and SB24 injection rates were 19.7 and 150 lb/hr, respectively. Injection rates are for the entire unit.

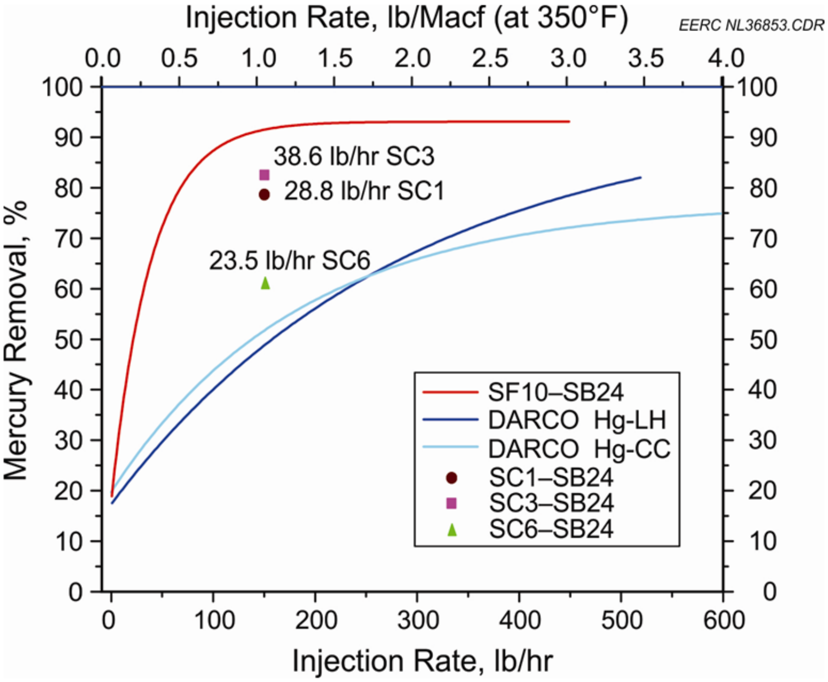


Figure 13. Summary of alternate SEA injection results compared to other technologies tested. Note: SC3–SB24 mercury removal was increased by 5% to reflect stack mercury removals. Injection rates are for the entire unit.

Hoot Lake Unit 2

While the primary goal of the testing at HL2 was to perform the ICR sampling to meet the requirements of EPA, additional testing was conducted to evaluate the performance of a mercury reduction technology and its effect on HAPs. Two days of parametric testing of a sorbent and an additive provided by Grünergy was conducted at HL2 following the ICR sampling. For the selected combination of SB24–SF10, it was indicated by Grünergy that the optimum combination for sorbent to additive is to maintain rates where the additive is injected at one-fifth the rate of the sorbent. This ratio was maintained during all injections. After an injection rate was found for approximately 80% mercury reduction, the injection rates were held constant during which flue gas sampling was conducted.

The Hg removals measured during parametric testing are shown in Figure 14. A few of the parametric rates were repeated, and the duplicates are also given. Three of these repeat tests are much lower than the original test. This is believed to be a change in mercury content of the coal and not from other variables. This coal displayed a high variability in mercury content based on analysis of the 12 samples collected during the injection testing. Also, the Hg removal curve based on the mercury content in the coal is lower than the curve generated from baseline ESP outlet mercury measurements. This lower removal value based on coal has been observed before at a few other plants, but an explanation has not yet been determined for this phenomenon.

Parametric testing indicated that 75% mercury removal can be achieved with a Grünergy sorbent/additive combination of 1.71/0.34 lb/Macf, respectively. Increasing the rate combination to 2.35/0.47 lb/Macf produced mercury removals above 85%, and greater than 90% removal was achieved with injection rates above 4.27/0.85 lb/Macf.

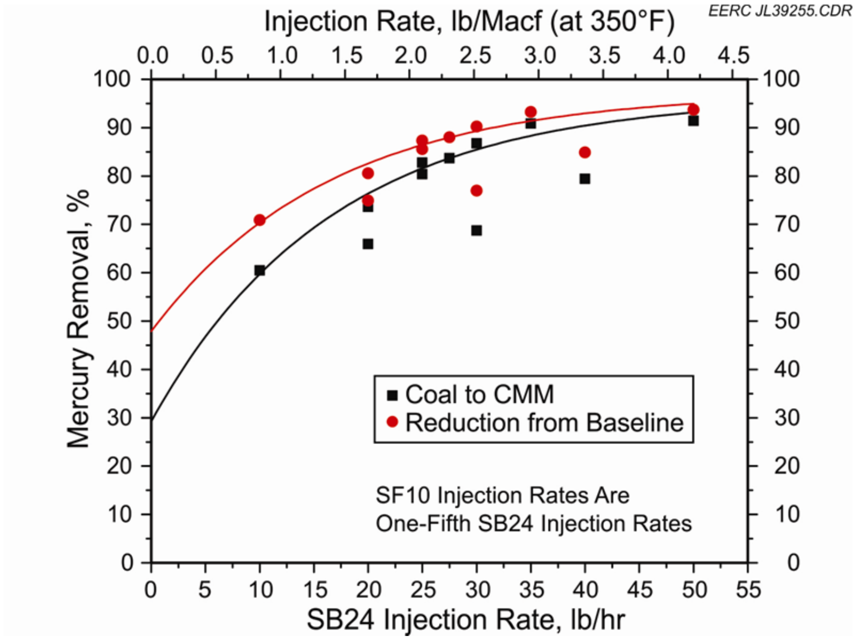


Figure 14. Stack percent mercury removals as a function of parametric SF10–SB24 injection rates. Injection rates are for the entire unit.

BALANCE-OF-PLANT RESULTS

Because of the short-term duration of the test programs compared to the operating life of the plants, truly long-term impacts of mercury control on the plant or its operations cannot be evaluated. Instead, more immediate changes were investigated. Daily plant operational data were downloaded by each plant and screened to determine if sorbent and/or SEA injection caused any changes in unit operations. No effect on plant operations at any of the sites was evident. At Mill Creek, it was determined there was negligible change in the mercury concentration in the gypsum and the concentrations remained within the salable range.

A more extensive evaluation of the balance-of-plant effects was conducted at Centralia. No effects directly related to the test program were documented for the duration of the project. Analysis of ESP hopper ash was collected during baseline, ET1, ET2, and ET3 saw an increase in the Hg fly ash concentrations which is consistent with the reduction in the flue gas mercury concentration. The Cl and Br concentrations in the ash also increased over baseline conditions. The loss on ignition (LOI) in the Koppers ESPs is similar to baseline conditions, but there is a significant increase in the Lodge ESPs because of sorbent injection. During ET3, the Lodge ESPs had a significant increase in Hg ash concentration, which is consistent with the observed flue gas measurements that showed the majority of the Hg was removed by the Lodge ESPs. The LOI increased in the Lodge ESPs, but this is due to the sorbent injection ahead of the Lodge ESPs.

Scrubber sampling was conducted daily at CENT2 during baseline and extended test conditions in order to determine the effects of sorbent injection on scrubber performance and FGD materials. Samples were collected from the reagent feed, recycle slurry, and gypsum. In the reagent feed and recycle slurry, mercury was analyzed for in both the liquid and solid portions. The baseline conditions show that the reagent feed is low in mercury. The majority of the mercury in the recycle slurry is in the solids. The gypsum mercury values are lower than the recycle slurry. The extended test data show that the mercury concentration in the recycle slurry is lower than the baseline conditions. The reason for this is due to the increase in mercury removal across the ESPs during the extended tests compared to baseline conditions. The mercury concentration in the FGD gypsum is consistent with baseline data. The slightly lower recycle slurry mercury concentration and the similar gypsum mercury concentration indicate that there is no significant impact on scrubber mercury concentrations and FGD materials as a result of the SF10–SB24 extended tests.

EPA Method 29 sampling was also conducted at CENT2 during baseline and extended testing to determine any effect that sorbent injection may have on stack trace metal emissions. The sampling occurred at the south Lodge inlet and the stack. The coal samples on the corresponding sampling days were also analyzed to determine the HAP concentrations in the coal. These concentrations were converted to a flue gas basis using a combustion calculation spreadsheet. The data show that the majority of the HAPs are removed in the Koppers ESPs, with additional removal in the Lodge ESPs and scrubber. Based on coal-to-stack measurements, >99% removal is obtained for all of the HAPs tested. Based on the data, sorbent injection for mercury control exhibits a very slight increase in removal for some of the HAPs tested.

EPA Method 5 sampling was conducted during baseline and extended testing at CENT2 to determine any effect that sorbent injection may have on increased stack particulate emissions. The data show little to no impact on the dust loading at the stack.

EPA M26a sampling was conducted during baseline, DARCO Hg-LH parametric testing, and SF10–SB24 ET3 to determine any the potential effect that SEA/sorbent injection may have on stack Cl, Br, and F emissions. The sampling occurred at the south Lodge Cottrell (LC) inlet and the stack. The baseline values at both the LC inlet and stack were below the detection limit of the method. The detection limits vary slightly because of variances in unit flow, coal composition, and load. The concentrations during DARCO Hg-LH injection were also below the detection limit at both of the sampling locations. During RT3 (SF10–SB24 injection), the value at the LC inlet was just above the detection limit with a concentration of 1.1 ppmv, but the stack value was below the detection limit. All of the flue gas F concentrations were below the detection limit for each of the test periods. These results show no significant increase in Cl and Br emissions as a result of sorbent injection.

At the request of plant personnel, a test was conducted to monitor the effects of TIFI® (targeted in-furnace injection) on mercury control. TIFI is a furnace additive designed to reduce slag on the furnace boiler walls. In order to assess the effects of TIFI injection, SF10–SB24 was continuously injected at rates of 35.1 and 150 lb/hr for a 24-hr period before TIFI was turned on. This allowed the mercury removals across the system to reach a steady state and track the stability of the mercury removal before the TIFI was turned on. There was little or no effect (positive or negative) as a result of TIFI with respect to mercury removal. The CMM data remained consistent for the time duration before and after TIFI.

Because of the unique ESP–ESP–wet FGD configuration at CENT2 and the sorbent injection location, the potential for self-heating of the ash/carbon in the hopper exists. When sorbents are exposed to typical flue gas temperatures and an oxidizing atmosphere, they will oxidize and generate heat at a rate that is strongly temperature-dependent. If the heat cannot be dissipated, the temperature of the sorbent will rise and eventually reach the sorbent's ignition temperature. The risk for self-heating depends on many intensive and extensive properties including:

- Concentration of the sorbent in the fly ash.
- Thermophysical properties of the material.
- Heat generation characteristics of the material.
- Material volume and geometry.
- Temperature and thermal boundary conditions.

Both flue gas temperature and sorbent content in the fly ash have a significant impact on the risk for self-heating. The use of hopper heaters will also increase the risk of self-heating. The flue gas temperature in the Lodge ESP is approximately 350°F. The sorbent content in the ash was calculated based on the amount of sorbent injected relative to the amount of ash entering the Lodge ESPs. The average amount of ash entering the Lodge ESPs is approximately 3500 lb/hr based on mass balance and dust loading calculations. The only case where self-heating was even considered a risk was during the injection of the DARCO Hg-LH sorbent at a rate of 475 lb/hr.

This was the rate required to achieve 80% mercury capture. At this injection rate, the ash sorbent content is approximately 12%. Even though 12% carbon in the ash is considered stable, the higher sorbent content in the ash will have a slightly higher probability for self-heating. Generally speaking, fly ashes that contain 10% or more carbon are considered at-risk, and extra precautionary measures should be taken to monitor and evacuate the hoppers on a more frequent and managed basis.

CCP samples from both the north and south Lodge ESPs were evaluated for the leachability of select constituents using the "Integrated Framework for Evaluating Leaching in Waste Management and Utilization of Secondary Materials" (19) method which has been adopted by EPA for the evaluation of CCPs. The maximum HAP leachate concentrations that were measured under the different test conditions were much lower than the TCLP limits regardless of the leachate pH. The maximum leachate concentrations for each HAP generally occurred toward either the more acidic or basic sides of the pH range. In addition to the HAPs discussed above, concentrations of select nonmetal analytes of interest, including Br, Cl, F, and SO_4, were also determined in the leachate samples. The Br, Cl, and F leachate concentrations remained low for each of the CCP samples. The SO_4 leachate concentrations were higher than the other nonmetals, with a range of approximately 100–2700 mg/L.

ICR Testing

The EERC performed gas sampling at HL2. The EERC successfully completed the required sampling to meet EPA requirements and assisted Otter Tail Power in compiling the information into the EPA's electronic reporting tool (ERT). The completed ERT data were submitted to EPA August 2010.

EERC staff returned to Hoot Lake and performed parametric testing of Grünergy sorbent/additive technology and performed gas sampling of selected acid gas HAPs, metallic HAPs, and particulate. A mercury removal target of 80%–85% was selected for constant injection during flue gas sampling. The injection rate for sorbent/additive was 2.13/0.43 lb/Macf, respectively. Sampling using EPA Methods 26a, 29, and combined OTM 27/28 for the collection of HAPs data was conducted over a 4-day period. The selected injection rate did maintain an average removal within the target range, but mercury concentration in the flue was variable.

Comparison of the data with the identical sampling conducted during the ICR portion of the project agreed with past work in that the resultant concentrations of HAPs were highly variable. Most of the metallic HAPs were unchanged except for beryllium and cobalt, which did decrease, and selenium, which actually increased concentration during sorbent/additive injection. Hydrogen fluoride concentration also increased. Total filterable particulate loading and filterable $PM_{2.5}$ decreased; however, inorganic and organic condensables increased.

Partitioning of the particulate and gaseous phase contributions of these sampling techniques were not evaluated in this project, but further work needs to be done to evaluate them. This project also developed results that were highly varied from one test run to another for each parameter. Further testing with a much more intense sampling strategy should be employed to better reduce uncertainty.

Analysis of Mineralogy in CCPs

Two recent research topics of interest on CCPs are emission control technologies and appropriate leaching tests. Mercury emission control technologies at coal-fired power plants are known to alter CCPs. Research has focused on the chemical aspects of these CCPs, with physical and mineralogical analyses limited in comparison. Not only is the total concentration of mercury increased in the solid CCP samples, the concentrations of other elements such as arsenic and selenium can change (20–24). EPA is recommending CCP leaching tests based on a method developed by Kosson and others (19), which includes a series of tests with the addition of an acid or base that could affect the leaching mechanisms of CCPs. A variety of subtasks were performed to initiate the use of mineralogical analyses to aid in the interpretation of previous laboratory investigations at the EERC.

Prepare Mortar or Paste Mixtures

The use of additives for mercury emission control can affect a fly ash such that it can no longer be used as an additive for cement replacement in concrete. For example, the use of an AC may increase the LOI value beyond the acceptable range and increase the level of air entraining agent required. Work performed under the EERC Coal Ash Resources Research Consortium® (CARRC®) Program showed that four of nine mercury emission control fly ash samples passed all ASTM C618 physical testing and foam index testing, which are used to indicate suitability as a mineral admixture in cement. The limited physical performance testing performed on nine samples of fly ash from mercury emission control demonstrations using AC and other material types alone or in combination showed that testing is needed to determine whether a particular sample can be used in concrete applications (25). Two of the mercury air emission control testing samples from the CARRC project plus a corresponding standard fly ash, which had not been tested, were chosen for evaluation of cementitious reactions in a cement paste. The CCPs were generated using a blend of Gulf Coast lignite and PRB subbituminous coals.

A maximum limit on SO_3 content is specified for fly ash as an additive in concrete to avoid an excess of this constituent in the hardened concrete that could contribute to a disruptive mineral transformation such as the formation of excessive amounts of ettringite (26). Ettringite forms rapidly when the pH is high and the components are available. The force of crystallization due to latent ettringite formation may cause concrete to fail. The SEM analysis did not find any ettringite in the paste samples. Shrinkage cracks were evident but no signs of expansion were noted. All of the chemistries were calcium silicate with variable amounts of Al, Mg, and Fe. The point chemical data collected by SEM shows that in the particles analyzed, sulfur is a minor component.

Figure 15 is a backscattered electron image showing a representative view of the polished surface of the paste cylinder sample containing the standard fly ash. The lighter, irregularly shaped particles are calcium aluminates and the slightly darker grey material often surrounding those particles has a higher Si content. Spherical fly ash particles can be readily seen throughout the sample.

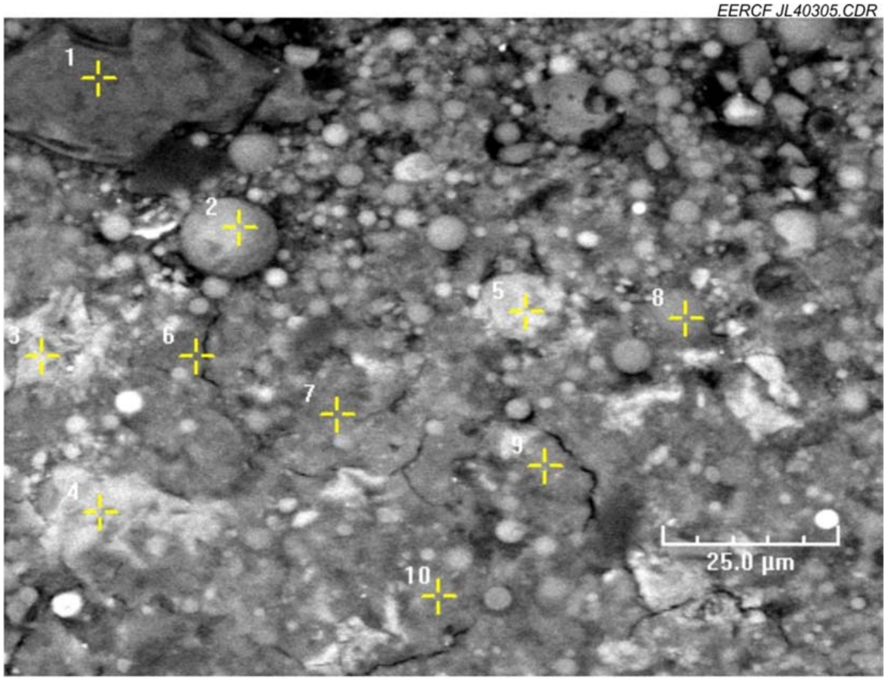


Figure 15. Standard fly ash–cement paste cylinder (1000x).

In Table 14, the first two analyses represent the light-colored material with high Ca and Al and a small amount of Fe and Si. The last three analyses represent the dark grey material often found surrounding the particle high in Ca and Al. Of particular interest is the relatively low sulfur in all point analyses taken. These sulfur amounts are too low for ettringite formation; 15% to 20% by weight of sulfur is required for ettringite formation.

Figure 16 shows the CCP–cement paste cylinder containing fly ash with ACI for mercury emission control. The darkest particles are the AC and the light grey to nearly white particles are primarily calcium silicates with small amounts of aluminum. Table 15 shows chemical analyses from the cement paste sample containing fly ash and AC. The nearly white particles are represented by those analyses with the highest calcium values, such as Tag 4 with 73 wt% Ca. Fly ash spherical particles can readily be seen as well.

Table 14. Chemical Analyses of Specific Points from the Standard Fly Ash–Cement Paste

Tag	Mg	Al	Si	S	K	Ca	Ti	Fe
1	2.57%	17.34%	8.90%	0.56%	0.05%	54.39%	0.95%	15.25%
2	0.59%	12.08%	15.20%	6.38%	0.63%	60.37%	0.56%	3.91%
3	2.28%	11.28%	49.59%	0.93%	3.03%	27.49%	0.58%	4.05%
4	0.90%	11.58%	31.96%	2.64%	1.23%	46.11%	0.47%	5.07%
5	1.02%	10.89%	29.73%	2.22%	1.39%	49.61%	0.55%	4.35%

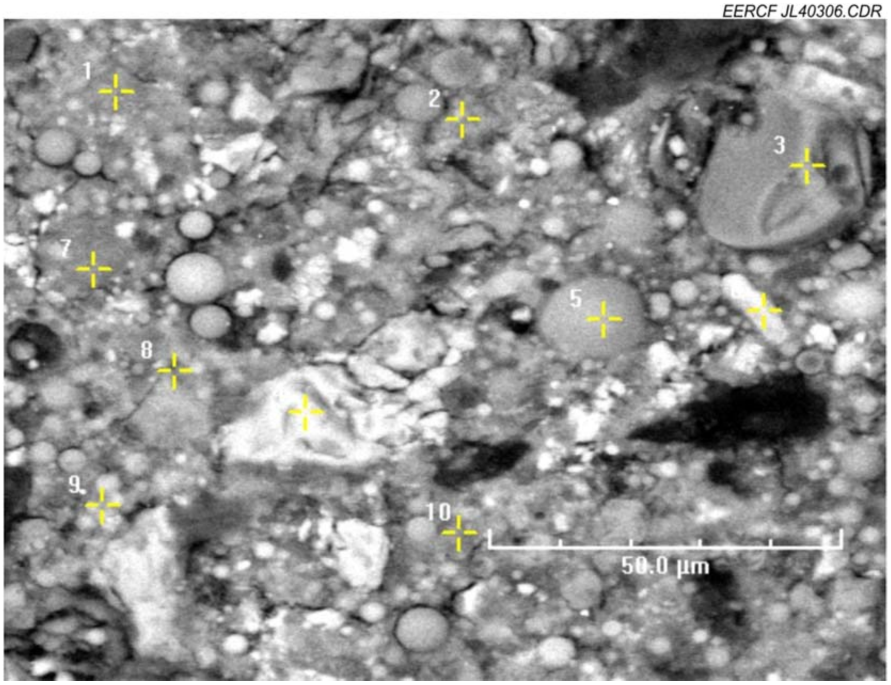


Figure 16. Cement paste with fly ash containing AC (1000x).

Table 15. Chemical Composition of Particles from the Fly Ash and AC–Cement Paste Sample

Tag	Mg	Al	Si	S	K	Ca	Ti	Fe
1	1.10%	11.24%	17.19%	4.76%	0.57%	60.46%	0.27%	4.24%
2	1.41%	6.08%	25.34%	3.45%	0.46%	59.76%	0.24%	3.25%
3	1.23%	25.92%	46.95%	0.51%	0.68%	21.30%	0.51%	2.79%
4	0.86%	2.33%	21.12%	0.52%	0.00%	73.34%	0.17%	1.30%
5	2.97%	20.81%	37.65%	0.38%	0.74%	29.43%	0.87%	6.93%
6	0.49%	2.98%	20.26%	0.96%	0.28%	73.25%	0.22%	1.36%
7	1.18%	4.38%	25.47%	2.04%	0.31%	65.04%	0.00%	1.58%
8	1.14%	5.25%	24.71%	3.19%	0.30%	63.21%	0.00%	1.97%
9	0.73%	6.95%	27.75%	2.93%	0.38%	58.02%	0.31%	2.84%
10	0.95%	9.20%	17.69%	5.65%	0.41%	60.61%	0.38%	4.94%

Figure 17 shows the cement paste sample made with fly ash resulting from the injection of AC and SEA4 for Hg control. The lighter grey particles are high in calcium, and the black particles are the AC particles. The very bright white “dots” are very high in iron. Table 16 shows the chemical composition of a variety of particles found in this sample.

There appears to be little physical and chemical difference, with the exception of carbon, in the three CCP–cement paste samples. The chemical compositions show that calcium silicates and calcium aluminum silicate are the major mineralogical phases that developed as expected in a cement matrix. Many of the fly ash particles themselves remained unchanged. From the chemical data collected, the apparent limited amounts of sulfur and aluminum played a role in ensuring ettringite is not readily forming.

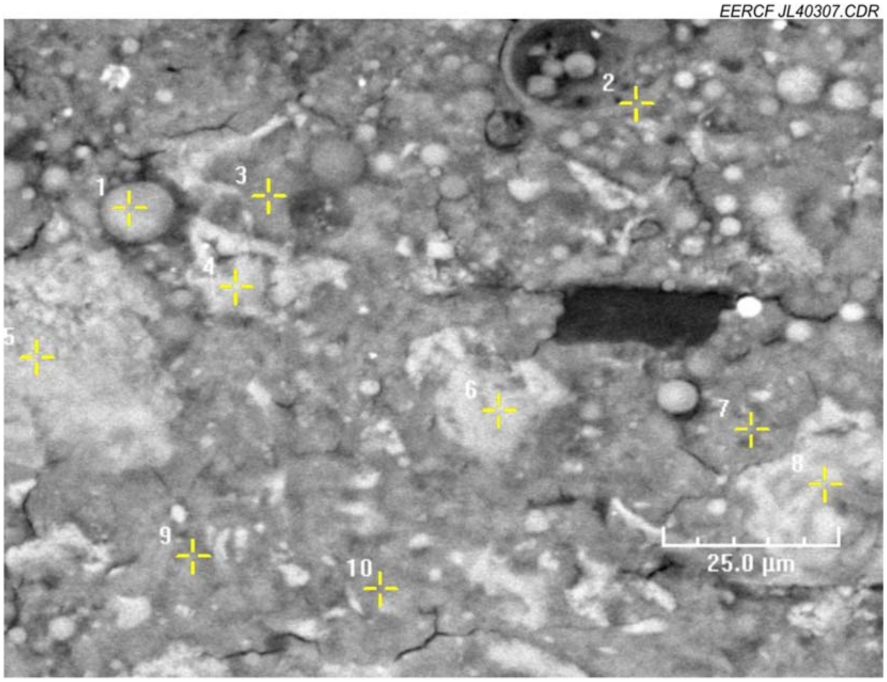


Figure 17. Cement paste with fly ash, AC, and SEA4 (250x).

Table 16. Chemical Composition of Particles Represented in the Fly Ash, AC, and SEA4–Cement Paste Sample

Tag	Mg	Al	Si	S	K	Ca	Ti	Fe
1	7.07%	25.76%	17.68%	1.01%	0.15%	35.58%	1.10%	10.40%
2	1.04%	19.20%	54.86%	1.01%	3.40%	16.17%	0.60%	3.73%
3	0.56%	4.43%	25.41%	3.05%	0.37%	63.45%	0.19%	2.53%
4	0.21%	3.09%	25.15%	1.11%	0.27%	67.58%	0.33%	1.96%
5	2.10%	8.53%	16.84%	1.02%	0.10%	64.90%	0.30%	6.02%
6	0.65%	2.08%	20.17%	0.53%	0.13%	74.60%	0.01%	1.56%
7	0.48%	3.78%	22.26%	2.80%	0.13%	68.83%	0.00%	1.71%
8	0.93%	2.02%	21.14%	0.44%	0.02%	73.97%	0.00%	1.26%
9	0.71%	3.97%	16.01%	3.17%	0.41%	72.60%	0.00%	2.93%
10	0.88%	3.64%	21.14%	4.14%	0.33%	67.57%	0.00%	1.92%

Leach Mercury Emission Control and Corresponding Standard CCPs

It has been noted in laboratory testing at the EERC that, in some instances, the bulk pH of a CCP has been reduced by the introduction of mercury control sorbents. This reduction in pH changed the leaching profile from that of decreasing concentrations in the leachate over time for elements such as arsenic, chromium, and selenium in the standard CCP to a leaching profile of increasing concentrations of these elements over the same leaching duration in the mercury emission control CCP (22). Short- and long-term leaching was used on a set of Fort Union lignite CCPs previously evaluated for trace element leachate trends (Samples H1 [standard CCP] and

H2 [mercury control testing CCP]) (22). Selected samples were analyzed using SEM techniques to determine if changes in the morphology occurred with the introduction of water.

The mineral ettringite is the primary hydration phase that is seen during the reaction of alkaline CCPs with water (27, 28). Ettringite is both an individual mineral, calcium aluminosulfate hydroxide hydrate [$Ca_6Al_2(SO_4)_3(OH)_{12}\cdot 26H_2O$], and the family name for a series of related compounds. Ettringite is unique in that several elements that exist as oxyanions present at high pH can substitute for the sulfate in the structure and exhibit a change in leaching profile with time. These elements include but are not limited to arsenic, boron, chromium, molybdenum, selenium, and vanadium. The basic requirements for the formation of ettringite in a solution or a paste are the presence of soluble sources of Ca, Al, and SO_4 and a pH of between 11.5 and 12.5. CCPs exhibiting a high bulk pH (<10.5) have the potential to undergo hydration reactions that can change the leaching profile with time (21, 28, 29). The 24-hour bulk pH of the samples used in this effort was near 12 for the standard fly ash and 10.5 for the mercury emission control CCP, which indicated the potential for ettringite formation.

In a test developed at the EERC to determine the expansion potential of CCPs, samples are hydrated for varying periods, filtered, oven-dried at <48°C to remove free water but not destroy the ettringite structure, and evaluated for density changes (30). SEM analyses were not performed in that work to verify the presence of ettringite. As indicated previously, the leached and filtered CCP samples in the present work were oven-dried at <36°C for added insurance in preparation for mineralogical analyses.

To evaluate a longer period of hydration, the 30-day LTL samples were selected for analysis using SEM. The leachate pH values were near 12 for the standard fly ash and approximately 11 for the mercury control testing CCP, which indicated the potential for ettringite formation but more likely in the standard fly ash. CCP samples were prepared for SEM analyses by putting them on double-stick carbon tape fixed onto a carbon sample stub. The samples were then carbon-coated for chemical analysis and imaging. SEM results show the presence of ettringite in the standard fly ash sample and no visible ettringite in the CCP from mercury control testing. The samples were analyzed as described in the methods section.

Figures 18 and 19 are SEM images of the 30-day LTL samples. The standard fly ash sample (Figure 18) is not as cemented into clumps as the Hg control CCP sample (Figure 19). Needlelike ettringite crystals are clearly visible in the standard fly ash sample and were common (Figure 18) and could not be found in the Hg control CCP sample (Figure 19). The formation or lack of ettringite was the fundamental difference both physically and chemically in these two samples. The mechanism of the Hg control material that inhibits ettringite formation is not known from this work. Since the physical appearance of the CCPs shows little difference even after a 30-day leaching procedure, it is likely that the addition of the Hg control material causes an alteration of the pH outside of the favorable conditions for ettringite formation rather than another phase competing for the same components such as the sulfate. These results are consistent with the trace element leaching profiles observed in previous leaching efforts; e.g., the standard fly ash Cr leachate concentration decreased with time while the mercury control testing CCP Cr leachate concentration increased with time (22).

EERC JL40283.CDR

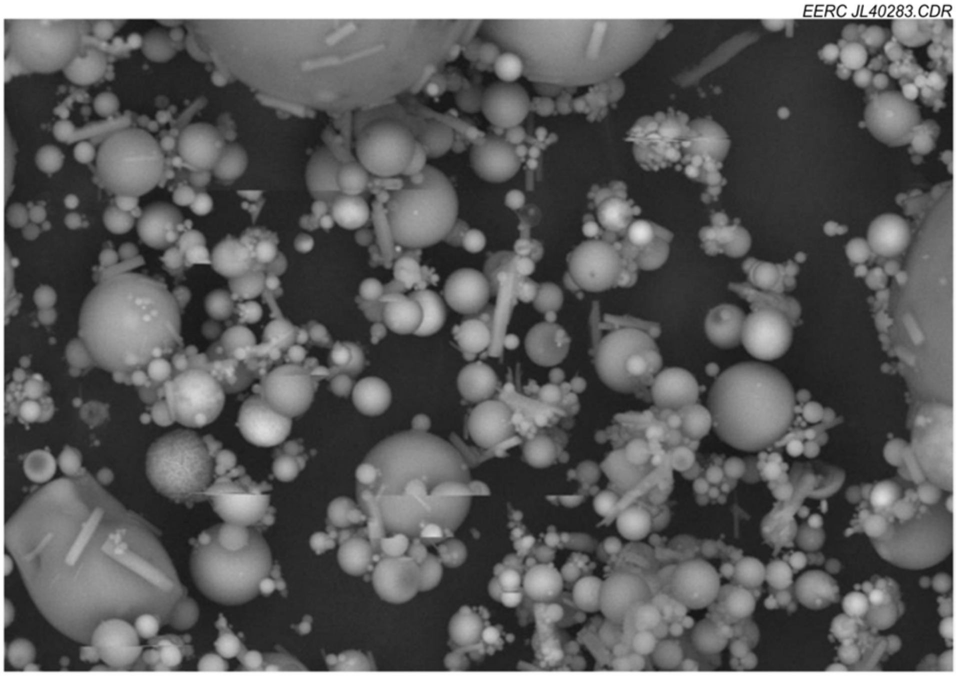


Figure 18. SEM image of standard fly ash after 30-day LTL (2500x).

EERC JL40284.CDR

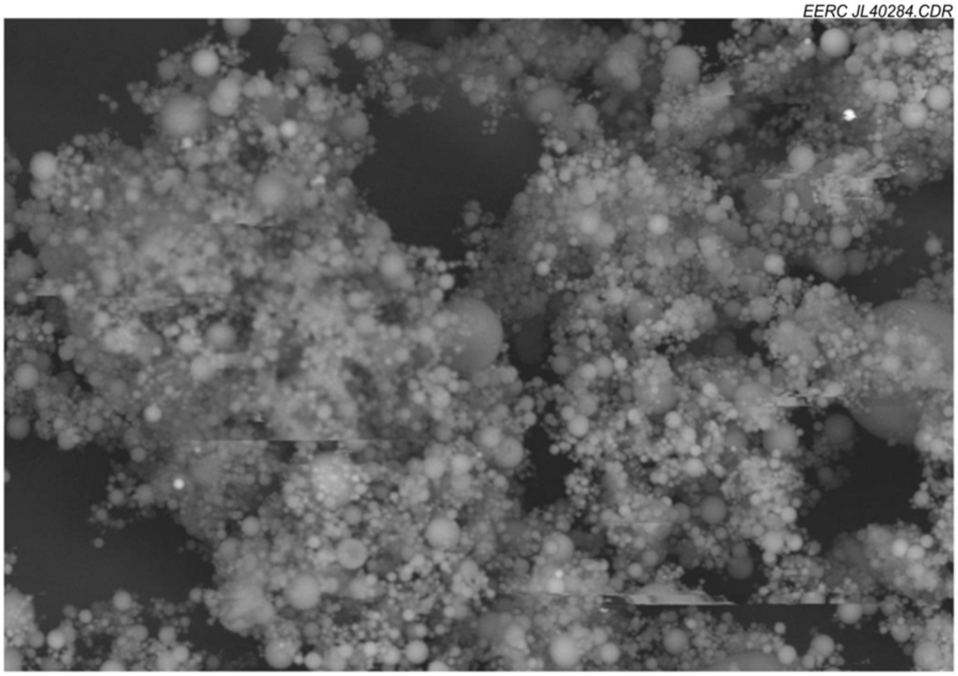


Figure 19. SEM image of Hg control CCP after 30-day LTL (2500x).

Alter the pH of the Leaching Solution with 1 N Potassium Hydroxide

Past work with the addition of 1 N KOH intended to increase the pH of a CCP leachate has shown trace element leachate results that indicate delayed ettringite formation. Under this task, a standard subbituminous CCP sample was leached at the natural pH and with the addition of 1 N KOH over 24-hr and 30-day equilibration periods. The solids remaining from the leaching tests were analyzed with SEM to determine if ettringite formation appeared to be delayed with the addition of 1 N KOH.

In the previous work with this sample, the bulk pH of the solid fly ash sample was 11.4. The titration pretest was used to determine the amount of 1 N KOH that would be needed to raise the pH to 12. After 24 hours of leaching, the leachate pH values were approximately 12 for the natural pH test. In the sample with the addition of 1 N KOH, the leachate pH increased to near 13.5. Following a 30-day leaching, the pH values were about 12.7 and 13.6 for the natural and 1 N KOH samples, respectively. The pH values alone indicate that ettringite formation is highly possible in the samples leached with distilled, deionized water. Conversely, the leachate pH values from the samples with the addition of 1 N KOH suggest that the pH is too high on a macroscale for ettringite formation.

The samples subjected to the two 24-hr tests were chosen for analysis by SEM because the 30-day samples did not show a significant additional change in pH value. The samples were prepared and analyzed as described in the methods section. After 24 hours of hydration at the natural pH (with distilled, deionized water), ettringite was found to have readily formed. Figure 20 shows ettringite needles forming in the fly ash. Along with the ettringite needles visible in Figure 20, some of the smaller ash particles appear to be forming a cement matrix around larger particles. Table 17 shows point chemistries primarily of the ettringite needles.

Figure 21 shows the fly ash sample with the 1 N KOH additive intended to increase the pH to 12. Very small needle- and bladelike crystals formed but were smaller than any ettringite crystals previously analyzed. The widths of these small crystals are considerably smaller than the width of the electron beam making chemical analyses of just that phase impossible by EDS methods. Table 18 shows particle chemistries from the fly ash with the added 1 N KOH. Calcium and aluminum were found to be in sufficient quantities for ettringite formation, but sulfur was relatively low. Potassium shows a slight elevation over the natural pH fly ash analyses in Table 17. Alunite [$KAl_3(SO_4)_2(OH)_6$] was not positively identified in this sample, but its formation would explain the lack of ettringite by using the available aluminum and sulfate.

Results show significant ettringite formation from the natural pH leaching test, while limited ettringite formation was evident from the leaching test with the addition of 1 N KOH to the leaching solution. These results are consistent with the leachate pH values and with the trace element leaching results from the previous leaching effort, which indicated inhibited ettringite formation with the addition of 1 N KOH because of the increase in pH beyond 12, which was the goal of the pretest titration, and beyond 12.5, which is the upper limit for ettringite formation. Additionally, the addition of KOH may have decreased the availability of aluminum and sulfate for ettringite formation.

Figure 20. Fly ash after 24 hours of hydration at natural pH showing ettringite formation (2500x).

Table 17. Particle Chemistry of Fly Ash after 24 hours of Hydration at Natural pH by EDS

Spectrum	Na	Mg	Al	Si	P	S	Cl	K	Ca	Ti	Fe
1	2.43	7.74	17.94	22.06	1.48	4.79	1.52	ND*	33.01	1.84	4.7
2	0.21	8.03	13.69	16.91	3.03	9.65	0.46	0.43	37.98	3.45	5.08
3	2.68	6.16	17.22	10.78	0.52	11.95	0.09	0.62	46.28	ND	0.77
4	2.14	6.07	24.81	12.82	2.54	5.88	0.01	0.55	37.82	10.02	6.54
5	2.28	29.91	24.51	5.47	2.08	1.88	0.76	0.31	26.39	0.18	6.35
6	4.32	6.26	24.83	32.01	0.24	1.27	ND	ND	25.57	ND	4.54

* Not detected.

Analyze Mercury Emission Control and Corresponding Standard CCPs

As discussed earlier, mercury emission control technologies at coal-fired power plants are known to alter the chemistry of CCPs. In this task, CCPs were analyzed with SEM to determine the presence of morphological changes with the use of mercury emission control technologies. A set of as-received subbituminous samples, consisting of a mercury control testing CCP (with injection of undisclosed additives or sorbents) and a corresponding standard CCP, were analyzed. The samples were prepared and analyzed as described in the methods section.

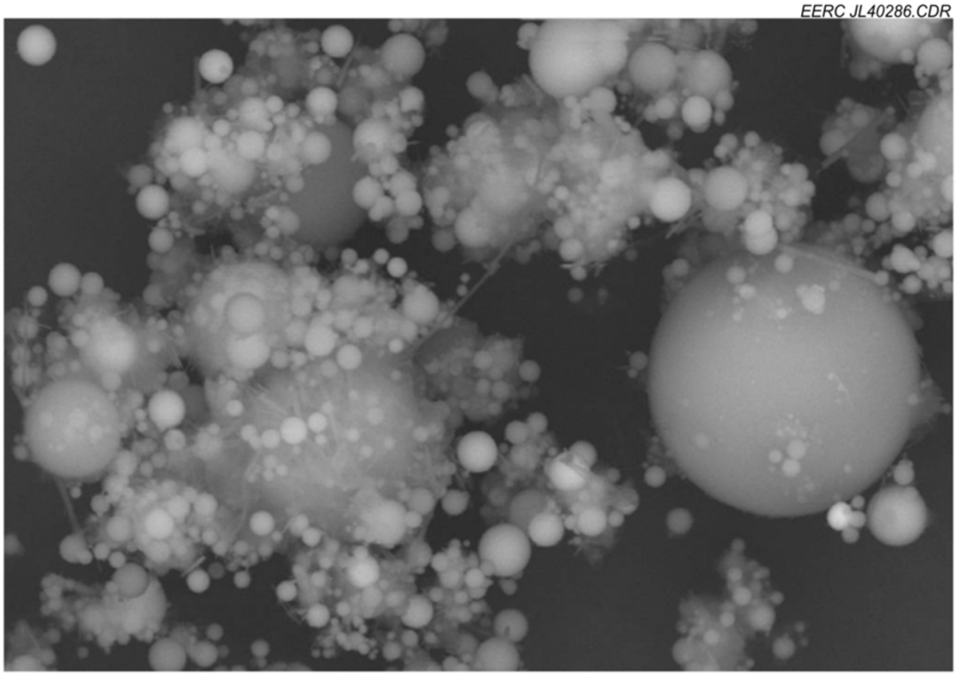


Figure 21. Fly ash after 24 hours of hydration with leaching solution containing 1 N KOH (2500x).

Table 18. Chemical Compositions of Fly Ash Particles after 24 hours of Hydration with Leaching Solution Containing 1 N KOH by EDS

Spectrum	Na	Mg	Al	Si	P	S	Cl	K	Ca	Ti	Fe	Ba
1	6.91	5.84	9.55	46.05	0.24	1.82	0.67	1.79	20.1	ND	5.18	2.1
2	3.19	10.33	15.38	23.28	3.1	2.92	0.35	1.49	31.99	0.4	9.22	ND
3	0.97	8.28	18.05	16.76	2.26	4.36	0.77	2.08	40.1	2.99	4.25	ND
4	0.97	8.58	20.79	13.44	1.68	4	ND	0.61	37.41	ND	9.08	4.38
5	1.33	8.81	17.66	18.21	3.18	1.78	0.47	1.61	36.52	1.46	6.08	2.88
6	5.4	7.04	26.97	24.55	1.43	2.48	0.69	1.59	27.74	2.69	4.91	ND
7	0.5	7.94	22.4	13.6	1.87	0.1	0.59	0.14	43.04	3.05	7.09	ND
8	0.38	14.09	12.31	12.42	1.34	1.68	0.35	ND	47.11	1.88	8.63	0.08
9	4.33	7.62	17.34	12.34	4.92	1.58	0.27	1.41	41.89	2.08	6.13	0.1
10	ND	8.91	19.49	13.95	1.26	5.96	0.39	2.03	48.22	3.39	3.72	ND

The as-received standard fly ash sample showed a highly variable size range of particles as can be seen in Figure 22. Particle sizes range from submicrometer to 30+ μm in diameter. All particles are spherical, and few are fused together. Many of the smaller particles tend to adhere to the larger particles.

Table 19 shows particle chemistries from the as-received standard fly ash sample. Of particular interest is the amount of Ca, Al, and S. Sulfur contents appear to be relatively low from these analyses but do not reflect a total sulfur content. Sulfur is commonly found as a coating compound on fly ash particles, often as a condensate on the surface while the particle

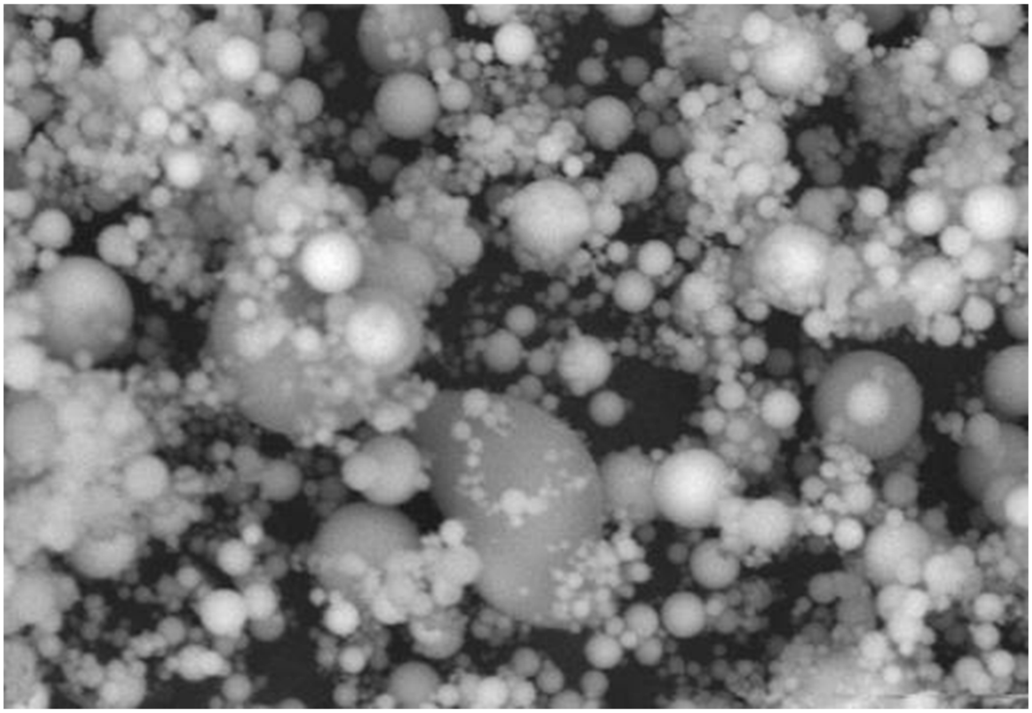


Figure 22. SEM image of the as-received standard fly ash (1000x).

Table 19. Particle Chemistries of As-Received Standard Fly Ash by EDS

Spectrum	Na	Mg	Al	Si	P	S	K	Ca	Ti	Fe	Ba
1	6.37	2.91	3.27	69.11	1.95	3.05	2.29	7.93	ND	2.14	1.06
2	ND	3.05	16.69	1.35	25.79	ND	0.14	41.03	ND	3.78	9.35
3	0.75	6.69	12.82	12.18	ND	1.4	0.31	53.04	1.89	13.14	ND
4	ND	26.21	22.4	4.24	ND	4.79	ND	35.88	ND	7.17	0.83
5	1.64	7.06	17.32	20.55	2.42	1.58	0.33	42.47	1.87	4.34	0.03
6	ND	5.33	26.82	30.63	0.52	ND	0.03	33.26	0.69	2.04	1.77
7	0.32	0.09	0.45	94.82	ND	0.12	2.12	1.53	ND	0.42	2.13

was cooling. The electron beam is roughly tangential to the surface of a particle that may easily penetrate a fine sulfate coating, thereby underestimating the amount of available sulfur for ettringite formation. Ettringite formation will likely depend largely on the availability of the aluminum and possibly the amount of sulfur.

Figure 23 and Table 20 depict the SEM results for the as-received Hg control CCP. The primary difference between the standard fly ash and the Hg control CCP was the presence of some larger aluminosilicate particles. Chemical compositions of particles show that there is little difference between the two samples (Tables 19 and 20).

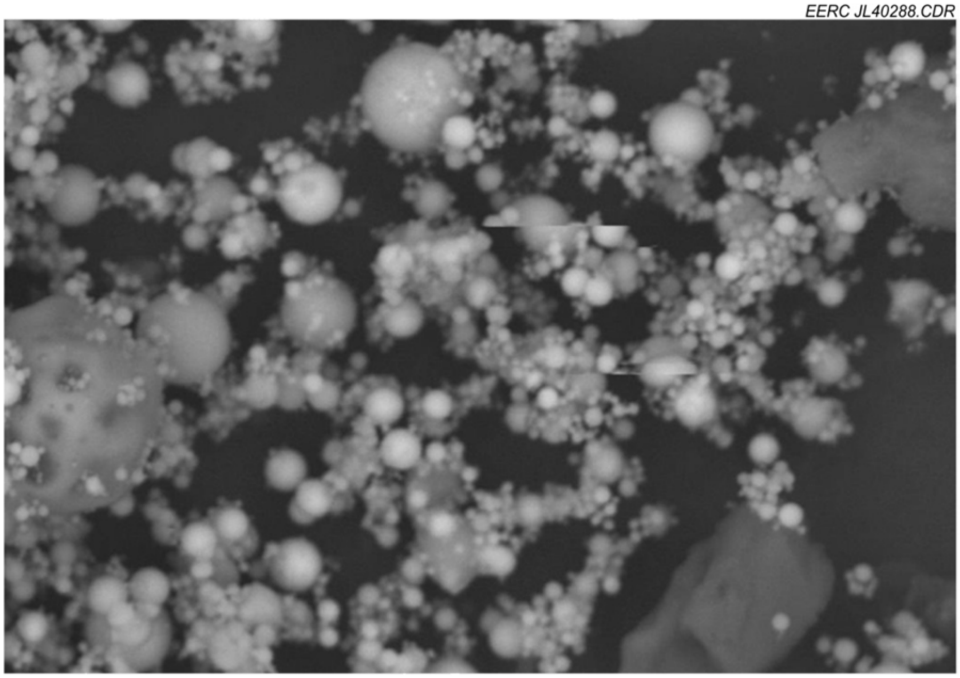


Figure 23. SEM image of as-received Hg control CCP (1000x).

Table 20. Particle Chemistry of As-Received Hg Control CCP by EDS

Spectrum	Na	Mg	Al	Si	P	S	Cl	K	Ca	Ti	Fe	Ba
1	8.65	2.57	20.89	48.16	ND	0.77	0.59	3.04	8.96	2.87	3.06	1.11
2	4.21	5.88	14.6	34.71	1.26	3.52	0.59	0.48	27.09	1.38	4.09	2.19
3	2.69	5.94	17.86	19.31	1.4	2.73	ND	1.01	39.44	1.38	6.99	1.7
4	3.48	7.76	19.67	14.27	1.87	5.2	0.84	0.53	35.56	1.63	7	2.2
5	7.6	5.05	20.75	32.1	1.13	3.18	0.61	1.82	20.35	0.47	5.34	1.6
6	4.39	5.75	18.83	29.01	0.41	5.01	0.49	0.82	29.3	1.25	3.89	0.86

CONCLUSIONS

Long-term demonstration tests of advanced SEA technologies have been completed at five coal-fired power plants. The targeted removal rate was 90% from baseline conditions at all five stations. The plants included Hawthorn Unit 5, Mill Creek Unit 4, San Miguel Unit 1, Centralia Unit 2, and Hoot Lake Unit 2.

Mill Creek 4

Baseline tests, followed by a suite of parametric tests, were conducted at the MC4 station in June 2007. It was found that the B&W additive added at the rate of 80 g/hr was capable of achieving >90% Hg removal from both baseline and from coal Hg levels. This technology was used for a 1-month, long-term study, and the average mercury removal efficiency of 91.8% was sustained without undue complications to the plant’s operation. Overall, the amount of reemission observed at MC4 was significantly lower than previously reported. PAC did not show any measurable improvement on the capture of mercury. This is not particularly surprising, since the coal has a high chlorine content, which combines with char to effect most of the elemental mercury oxidation that chlorine/PAC would be doing if the coal were low in chlorine content.

In addition to CMM and OH method measurements, EPA Method 30B (sorbent trap) measurements were also obtained for comparison with the CMM and OH method data. There was a surprisingly close agreement between sorbent trap and CMM results, which seems to suggest that sorbent traps are a potential, cheaper useful alternative to CMMs for making flue gas mercury concentration measurements. Detailed analysis of the coal properties revealed that the moisture content was low (<10%), but chlorine and sulfur levels were high (>1100 ppm and > 3%, respectively). The nitrogen content was about 1.5% on average, and the heating value was about 12,000 Btu. These values are consistent with what is known about typical eastern bituminous coals.

The long-term mercury control test had little impact on the gypsum mercury content. However, in theory, this should be the primary outlet for the additional captured mercury. This observation is probably due to the composite nature of the gypsum samples. Although the study period was relatively short, compared to the plant's lifetime, for any conclusions on the impact of Hg balance on the plant's operation to be drawn, our measurements indicate very low Hg levels in FGD gypsum sold to a wallboard company. Measurements obtained during the 1-month application of the B&W reemission additive show a reduction in the gypsum Hg content of at least 10% relative to previous levels reported by the plant. Hence, the gypsum continues to be salable in quality, especially after the application of the B&W scrubber additive.

Hawthorn 5

At HAW5, results of the parametric tests revealed that two possible technologies are capable of achieving more than 90% mercury removal from baseline and from coal mercury levels. These include addition of PAC (2 lb/Macf) in combination with Cl_2 (500 ppm) and the Norit Hg-LH additive (3 lb/Macf), which showed performances of 94% and 93%, respectively, from coal mercury levels (93 and 90%, respectively, from baseline mercury levels). Furthermore, addition of PAC (322 lb/hr) in conjunction with Cl_2 (1200 ppm) and the Norit Hg-LH (2 lb/Macf) each afforded 89% removal from coal mercury levels, and each of these was only about 3% short of 90% removal from baseline.

Substantial SCR catalyst blinding was observed at the Hawthorn Station, which led to lower oxidized elemental mercury levels. A limited number of sorbent trap measurements also showed reasonable agreement with CMM data. Detail analysis of the coal samples showed a relatively high moisture content (~20%) and very low chlorine, sulfur, and nitrogen levels (~15 ppm, <0.5% and <1%, respectively). Because of the higher amount of moisture, the average heating value was about 10,000 Btu. However, these properties are within the range that can be expected for typical PRB subbituminous coals.

San Miguel 1

At the San Miguel Station scrubber reemission remains a critical problem for the SMEC power plant and prevents the plant from obtaining a mercury capture of ≥90%. The B&W scrubber additive tested demonstrated little to no effect on scrubber emission compared to the data obtained in the absence of the scrubber additive.

The SF11–SB11 technology provided by RLP Energy demonstrated an 81.7% mercury removal across the plant at SF11 and SB11 injection rates of 80 lb/hr and 3.5 lb/Macf. This technology achieved results slightly better than other materials tested at SMEC and offers the potential to achieve ≥90% mercury capture if the scrubber reemission can be mitigated.

Centralia 2

Baseline, parametric, and extended tests were successfully conducted at the test unit for several mercury control technologies. The baseline test period indicated that the flue gas mercury concentration exhibits some variance but remains within a consistent range. Parametric test results indicated that SF10–SB24, SF10–SB21, and DARCO Hg-LH were able to achieve the target mercury removal of ≥ 80%. Because of its strong performance, SF10–SB24 was chosen for four extended tests, which targeted mercury removals of 60%, 70%, 80%, and >90%. The targeted mercury removal was exceeded for each of the extended tests.

In general, the ST measurements agreed well with the CMMs and typically were within a relative difference of 10%. The coal and inlet ST data agreed fairly well and demonstrated that either method can be used to determine the inlet flue gas mercury concentration. The baseline mercury removals indicated that little to no mercury was removed in the Koppers and Lodge ESPs, and 18.5% was removed in the scrubber for a total baseline mercury removal of 18.5%.

During SF10–SB24 injection, the Lodge ESPs captured most of the flue gas mercury, with an additional 5%–15% capture across the scrubber. During SF10–SB24 ET3, approximately 6.7% of the mercury was removed in the Koppers ESPs, 71.1% across the Lodge ESPs, and 16.8% across the scrubber for a total mercury removal of 94.6% based on mass balance calculations. Since the majority of the mercury is removed in the Lodge ESPs before it enters the scrubber, the total mercury in the scrubber and FGD materials decreases because of less mercury entering the scrubber as compared to baseline conditions. This is beneficial when considering FGD materials as a salable commodity.

The halogen (M26a) and trace element (M29) data showed little to no impact in stack emissions as a result of sorbent injection. The M26a data showed that the stack halogen emissions were less than 1.1 ppmv. The stack M29 data demonstrated >99% removal during baseline and injection testing periods. The Koppers ESPs removed 75%–95% of the trace metals, with the rest of the removal occurring across the Lodge ESPs and scrubber. The particulate (M5) data did not show any significant effect (positive or negative) due to sorbent injection when the data were compared to baseline results.

The impacts of TIFI on mercury removal were also evaluated. SF10–SB24 injection with and without the addition of the TIFI furnace additive demonstrated that TIFI does not have any impact (positive or negative) on mercury removal.

The self-heating risk in the Lodge ESP hoppers is minimal at low injection rates. The SF10–SB24 reduces the self-heating risk because the amount of injected carbon-based sorbent is minimized because of the performance of the technology. However, the use of treated carbons (i.e., from Norit Americas) will increase this risk as more than twice as much sorbent is needed to achieve similar mercury removals.

The alternate SEA technology was successfully tested during parametric and full-scale tests and demonstrated that this approach yields mercury removals up to 35% higher than treated AC injection at equivalent injection rates. When compared to the best front- and back-end approach, the alternate SEA technology demonstrates removals that are approximately 10% lower at equivalent injection rates. The parametric tests indicated that 70%–75% mercury removal was feasible at low injection rates. The 8-hr extended test demonstrated that the technology was able to obtain consistent mercury removals for an extended period of time.

In terms of testing the alternate SEA, the biggest challenge was testing within the limitations of the temporary rubber hose that was installed for sorbent injection. Future testing/installations need to overcome condensation issues by using metal piping and operating at higher temperatures, which are expected to result in improved performance.

The leachate data showed that 95%–99% of the HAP elements remained in the CCP samples and that the baseline sample data were similar to the ET1 sample data. The maximum leachate values were significantly below the TCLP leachate limits.

Hoot Lake 2

The ICR requirements for the HL2 were successfully met. The data were compiled and entered into the EPA ERT and submitted to EPA August 2010. This site was especially challenging because of plant configuration and port placement, but the challenges were overcome.

In addition, a mercury control technology provided by Grünergy was parametrically tested for its effectiveness. Results indicate that a mercury removal rate of 75% can be achieved across the ESP with the combination of a sorbent injection rate of 1.71 lb/Macf upstream of the AH and an additive injection rate of 0.34 lb/Macf into the boiler. It was determined that 85% reduction can be achieved with a combined injection of sorbent/additive of 2.35/0.47 lb/Macf, respectively. Greater than 90% removal can be attained but would require sorbent/additive injection rates above 4.27/0.85 lb/Macf, respectively.

Selected particulate, acid gas, and metallic HAPs were also sampled during a 4-day period, where the injection of sorbent/additive was maintained at a constant rate during the day but not at night. When the results were compared to values obtained during the ICR sampling, it was found that the overall total filterable particulate and filterable $PM_{2.5}$ loadings decreased, the inorganic and organic condensables increased, hydrogen chloride was unchanged, but hydrogen fluoride was significantly increased. The ash content of the coal did change between ICR and injection sampling, so direct effect of injection with particulate loading cannot be determined with just the three particulate tests conducted here. There have been anecdotal observations of particulate loading decrease across an ESP at a few other plants, but data have not been presented to the public to date. Metallic HAP concentrations varied widely but did seem to indicate that beryllium and cobalt did decrease. Selenium, however, appeared to increase. As expected, mercury concentrations decreased.

Partitioning of the particulate and gaseous-phase contributions of these sampling techniques were not evaluated in this project, but further work needs to be done to evaluate them. This project also developed results that were highly varied from one test run to another for each parameter. Further testing with a much more intense sampling strategy should be employed to better reduce uncertainty.

CCP Analysis

Two recent research topics of interest on CCPs are emission control technologies and appropriate leaching tests. Mercury emission control technologies at coal-fired power plants are known to alter CCPs. Research has focused on the chemical aspects of these CCPs, with physical and mineralogical analyses limited in comparison. The EPA is recommending CCP leaching tests based on a method developed by Kosson and others (19), which includes a series of tests with the addition of an acid or base that could affect the leaching mechanisms of CCPs. A variety of subtasks were performed to initiate the use of mineralogical analyses to aid in the interpretation of previous laboratory investigations at the EERC. The results of SEM analyses in the subtasks are as follows:

- Prepare mortar or paste mixtures: Additives utilized for mercury emission control can be detrimental to the use of fly ash as a cement replacement in concrete. Two mercury control test demonstration CCPs that passed ASTM C618 physical testing in a previous study exhibited cementitious reactions in paste form similar to the standard fly ash.

- Leach mercury emission control and corresponding standard CCPs: Previous SGLP and LTL profiles showed a shift from decreasing trace element concentrations over time from a standard fly ash to increasing concentrations over time from a corresponding mercury control testing CCP. The leaching profile provided indirect evidence that ettringite formation was responsible for the reduction in concentrations in the standard fly ash. These samples were leached again with results showing a significant decrease in the amount of ettringite present in the sample from mercury emission control testing, supporting the previous hypothesis.

- Alter the pH of the leaching solution with 1 N KOH: The addition of 1 N KOH, intended to increase the leachate pH of a material to 12, altered the leaching trend noted in some CCPs previously evaluated at the EERC. The results implied inhibited ettringite formation. One sample was chosen for mineralogical analyses following leaching at the natural pH with distilled, deionized water and with the addition of 1 N

KOH. The results showed a significant amount of ettringite formation in the natural pH sample, while limited ettringite formation was evident in the sample with the addition of 1 N KOH. An excessive pH increase and the presence of K contributed to the reduced level of ettringite formation.

- Analyze mercury emission control and corresponding standard CCPs: An as-received mercury control testing CCP and the corresponding standard CCP were analyzed for mineralogical differences. Chemical compositions of particles show that there is little difference between the two samples.

REFERENCES

1. Center for Air Toxic Metals. *Center for Air Toxic Metals Final Technical Report Volume IV*; Final Technical Report (Oct 15, 1999 – Sept 30, 2004) for U.S. Environmental Protection Agency Assistant Agreement R 827649-01; Energy & Environmental Research Center: Grand Forks, ND, Dec 2004.

2. Sondreal, E.A.; Benson, S.A.; Pavlish, J.H.; Galbreath, K.C.; Zygarlicke, C.J.; Thompson, J.S.; McCollor, D.P; Crocker, C.R.; Lillemoen, C.M.; Mann, M.D.; Jensen, R.R.; Weber, G.F. *Center for Air Toxic Metals Final Technical Report Volume 3*; Final Technical Report for U.S. Environmental Protection Agency Assistant Agreement R824854; Energy & Environmental Research Center: Grand Forks, ND, Sept 2000.

3. Pavlish, J.H.; Benson, S.A.; Zygarlicke, C.J.; Erickson, T.A.; Galbreath, K.C.; Schelkoph, G.L.; O'Leary, E.M.; Timpe, R.C.; Anderson, C.M. *Center for Air Toxic Metals Final Technical Report Volume 2*; Final Technical Report for U.S. Environmental Protection Agency Contract No. CR823173; EERC Publication 98-EERC-03-03; Energy & Environmental Research Center: Grand Forks, ND, April 1998.

4. Benson, S.A.; Pavlish, J.H.; Erickson, T.A.; Katrinak, K.A.; Miller, S.J.; Steadman, E.N.; Zygarlicke, C.J.; Dunham, G.E.; Pflughoeft-Hassett, D.F.; Galbreath, K.C. *Center for Air Toxic Metals Final Technical Report Volume 1*; Final Technical Report for U.S. Environmental Protection Agency Contract No. CR821518-01; Dec 1995.

5. Benson, S.A.; Crocker, C.R.; Galbreath, K.C.; Gunderson, J.R.; Holmes, M.J.; Laumb, J.D.; Mackenzie, J.M.; Olderbak, M.R.; Pavlish, J.H.; Yan, L.; Zhuang, Y. *Pilot- and Full-Scale Demonstration of Advanced Mercury Control Technologies for Lignite-Fired Power Plants*; Final Report for U.S. Department of Energy National Energy Technology Laboratory Cooperative Agreement No. DE-FC26-03NT41897; EERC Publication 2005-EERC-02-05; Energy & Environmental Research Center: Grand Forks, ND, Feb 2005.

6. Benson, S.A.; Mackenzie, J.M.; McCollor, D.P.; Galbreath, K.C. *Mercury Control Technologies for Electric Utilities Burning Subbituminous Coals*; Draft Multiclient Final Report, JV Task 73 (Jan 2, 2004 – June 30, 2005), for U.S. Department of Energy Cooperative Agreement No. DE-FC26-98FT40321; June 2005.

7. Benson, S.A.; Holmes, M.H.; McCollor, D.P.; Mackenzie, J.M. *Large-Scale Mercury Control Technology Testing for Lignite-Fired Utilities – Oxidation Systems for Wet FGD*; Technical Progress Report (April 1 – June 30, 2005) for the U.S. Department of Energy National Energy Technology Laboratory under DOE NETL Cooperative Agreement DE-FC26-03NT41991; July 2005.

8. Holmes, M.J.; Pavlish, J.H.; Thompson, J.S.; Wocken, C.A. *Enhancing Carbon Reactivity in Mercury Control in Lignite-Fired Systems*; Technical Progress Report for (April 1 – June 30, 2005) for the U.S. Department of Energy National Energy Technology Laboratory Cooperative Agreement DE-FC26-03NT41989; Aug 2005.

9. Holmes, M.J.; Pavlish, J.H.; Thompson, J.S.; Wocken, C.A. *Enhancing Carbon Reactivity in Mercury Control in Lignite-Fired Systems;* Technical Progress Report for (July 1 – Sept 30, 2004) for the U.S. Department of Energy National Energy Technology Laboratory Cooperative Agreement DE-FC26-03NT41989; Nov 2004.

10. Guo, X.; Zheng, C.G. Characterization of Arsenic Emissions from a Coal-Fired Power Plant. *Environ. Sci*. **2006**, *27*, 631–635.

11. Lopez-Anton, M.A.; Diaz-Smoano, M. Arsenic and Selenium Capture by Fly Ashes at Low Temperature. *Environ. Sci. Technol*. **2006**, *40*, 3947–3951.

12. Linak, W.P.; Wendt, J.O.L. Trace Metal Transformation Mechanisms During Coal Combustion. *Fuel Process. Technol*. **1994**, *39*, 173–198.

13. Seames, W.S.; Wendt, J.O.L. Regimes of Association of Arsenic and Selenium During Pulverized Coal Combustion. In *Proceedings of the Combustion Institute*; 2007; Vol. 31.

14. Helble, J.J. A Model for the Air Emissions of Trace Metallic Elements from Coal Combustors Equipped with Electrostatic Precipitators. *Fuel Process. Technol*. **2000**, *63*, 125–147.

15. Li, Y.; Tong, H.; Zhuo, Y.; Wang, S.; Xu, X. Simultaneous Removal of SO_2 and Trace SeO_2 from Flue Gas: Effect of SO_2 on Selenium Capture and Kinetics Study. *Environ. Sci. Technol*. **2006**, *40*, 7919–7924.

16. Miller, S.J.; Ness, S.R.; Weber, G.F.; Erickson, T.A.; Hassett, D.J.; Hawthorne, S.B.; Katrinak, K.A.; Louie, P.K.K. *A Comprehensive Assessment of Toxic Emissions from Coal-Fired Power Plants: Phase I Results from the U.S. Department of Energy Study*; Final Report for the Pittsburgh Energy Technology Center and the U.S. Department of Energy Contract No. DE-FC21-93MC30097 (Subtask 2.3.3); Energy & Environmental Research Center: Grand Forks, ND, Sept 1996.

17. ASTM D6784-02. Standard Test Method for Elemental, Oxidized, Particle-Bound and Total Mercury in Flue Gas Generated from Coal-Fired Stationary Sources (Ontario Hydro Method). ASTM International, West Conshohocken, PA, www.astm.org.

18. Hassett, D.J. Synthetic Groundwater Leaching Procedure, In *Encyclopedia of Environmental Analysis and Remediation*; Meyers, R.A., Ed.; John Wiley & Sons, Inc., 1998; pp 4797–4803;

19. Kosson, D.S.; van der Sloot, H.A.; Sanchez, F.; Garrabrants, A.C. An Integrated Framework for Evaluating Leaching in Waste Management and Utilization of Secondary Materials. *Environ. Eng. Sci.* **2002**, *19* (3), 159–203.

20. Dahl, A.L.; Gilmour, C.C.; Brickett, L.A. The Impact of Mercury Control Technologies on Mobility Pathways of Hg, Ni, As, Se, Cd, and Pb from Coal Utilization Byproducts. In *Proceedings of the EPA-DOE-EPRI-A&WMA Power Plant Air Pollutant Control Mega Symposium 2008*; Baltimore, MD, Aug 25–28, 2008.

21. Hassett, D.J.; Heebink, L.V.; Pflughoeft-Hassett, D.F.; Buckley, T.D.; Zacher, E.J.; Xin, M.; Gustin, M.S.; Jung, R. *Mercury and Air Toxic Element Impacts of Coal Combustion By-Product Disposal and Utilization*; Final Report (Jan 23, 2003 – Dec 31, 2006) for U.S. Department of Energy National Energy Technology Laboratory Cooperative Agreement No. DE-FC26-02NT41727, North Dakota Industrial Commission Agreement No. FY03-XLVIII-117, Duke Energy, Great River Energy, Utility Solid Waste Activities Group, and Electric Power Research Institute; EERC Publication 2007-EERC-10-03; Energy & Environmental Research Center: Grand Forks, ND, Oct 2007.

22. Heebink, L.V.; Pflughoeft-Hassett, D.F.; Hassett, D.J. Effects of Mercury Emission Control Technologies Using Halogens on Coal Combustion Product Chemical Properties. *JEM* **2010**, *12* (3), 608–613.

23. Pavlish, J.H.; Thompson, J.S.; Martin, C.L.; Musich, M.A.; Hamre, L.L. *Field Testing of Activated Carbon Injection Options at TXU's Big Brown Station*; Final Report for the U.S. Department of Energy, EERC Publication 2008-EERC-01–05, Energy & Environmental Research Center, Grand Forks, ND, April 2008.

24. Sanchez, F.; Keeney, R.; Kosson, D.; Delapp, R. *Characterization of Mercury-Enriched Coal Combustion Residues from Electric Utilities Using Enhanced Sorbents for Mercury Control*; Contract No. EP-C-04-023, Work Assignment 1-31, EPA-600/R-06/0008, Feb 2006.

25. Heebink, L.V.; Dockter, B.A.; Pflughoeft-Hassett, D.F.; Hassett, D.J. *Evaluation of Mercury Emission Controls on Coal Combustion Product (CCP) Engineering Performance*; Final Topical Report for CARRC Members; EERC Publication No. 2010-EERC-05-02; Energy & Environmental Research Center: Grand Forks, ND, May 2010.

26. EPRI. Impacts of Sodium-Based Reagents on Coal Combustion Product Characteristics and Performance. EPRI, Palo Alto, CA, and UND EERC, Grand Forks, ND, 2010, 1017577.

27. Hassett, D.J.; McCarthy, G.J.; Henke, K.R.; Korynta, E.D. Characterization of a Lignite Ash from the METC Gasifier III: Correlations with Leaching Behavior and Mineralogy. In *Fly Ash and Coal Combustion By-Products: Characterization, Utilization, and Disposal I*; McCarthy, G.J., Lauf, R.J., Eds.; Materials Research Society, Pittsburgh, PA, 1985.

28. Hassett, D.J.; Pflughoeft-Hassett, D.F.; McCarthy, G.J. Ettringite Formation in Coal Ash as a Mechanism for Stabilization of Hazardous Trace Elements. Presented at the 9th ACAA International Coal Ash Utilization Symposium, Orlando, FL, Jan 22–25, 1991.

29. Hassett, D.J.; Pflughoeft-Hassett, D.F.; McCarthy, G.J. Ettringite Formation in Coal Ash as a Mechanism for Stabilization of Hazardous Trace Elements. In *Proceedings of the 8th Annual International Pittsburgh Coal Conference*; Pittsburgh, PA, Oct 14–18, 1991.

30. Hassett, D.J.; Zacher, E.J.; Heebink, L.V. Determination of Expansion Potential of Coal Combustion By-Products. In *Proceedings of the World Coal Ash Conference*; Lexington, KY, April 11–15, 2005.

APPENDIX A

LONG-TERM DEMONSTRATION OF SORBENT ENHANCEMENT ADDITIVE TECHNOLOGY FOR MERCURY CONTROL – HAWTHORN

LONG-TERM DEMONSTRATION OF SORBENT ENHANCEMENT ADDITIVE TECHNOLOGY FOR MERCURY CONTROL

Final Report

(for the period of May 31, 2006, through August 31, 2008)

Prepared for:

AAD Document Control

U.S. Department of Energy
National Energy Technology Laboratory
626 Cochrans Mill Road
PO Box 10940, MS 921-107
Pittsburgh, PA 15236-0940

Cooperative Agreement No. DE-FC26-06NT42775

Prepared by:

Jason D. Laumb
Alexander Azenkeng
Dennis L. Laudal
Grant E. Dunham
Christopher L. Martin
Kevin C. Galbreath

Energy & Environmental Research Center
University of North Dakota
15 North 23rd Street, Stop 9018
Grand Forks, ND 58202-9018

2011-EERC-05-08

May 2011

EERC DISCLAIMER

DISCLAIMER

TABLE OF CONTENTS

LIST OF FIGURES ii

LIST OF TABLES iv

EXECUTIVE SUMMARY vi

INTRODUCTION 1

METHODS 3
- The Ontario Hydro Method 4
- Continuous Mercury Monitors 5
- Parametric Test Descriptions 5
- PAC Injection System 5
- SEA Injection Systems 7
- Long-Term Demonstration Test Descriptions 7
  - Coal, Ash, and Slurry Analyses 7

RESULTS AND DISCUSSION 8
- Hawthorn Unit 5 16
- Stack and SDA–FF Results – September 2006 Testing 18
- Stack and SDA–FF Results – December 2006 Testing 20
- Stack Results – July 2007 Testing 33
- Stack Results – November/December 2007 Testing 33
- Comparison of Tested Technologies 34
- Analysis of Coal and Ash Samples 34
- Mill Creek Unit 4 36
- Baseline Results 36
  - Coal Characteristics 37
  - Analysis of Flue Gases 37
  - Chloride and Sulfur Trioxide Levels 37
  - Analysis of FGD Thickener Streams and ESP Ash 38
  - Baseline Mercury Mass Balance 38
- Parametric Test Results 39
- Long-Term Demonstration Test Results 40
  - Sorbent Trap Results 40
  - Mercury Content in Other Process Streams 41
  - Long-Term Mercury Mass Balance 41
  - Impact of Mercury Mass Balance on the Plant 42

CONCLUSIONS 42

REFERENCES 44

ESTIMATION OF MASS FLOW RATES Appendix A

LIST OF FIGURES

1 Schematic of MC4 showing SEA/PAC injection points and sampling locations 3

2 Schematic of HAW5 showing SEA/PAC injection points and sampling locations............. 4

3 Schematic of ACI system 6

4 Simulated fluid flow distribution for an ACI system 6

5 Stack total Hg removal efficiencies of the various additives during September 2006 testing at HAW5 10

6 Plot of CMM data obtained at stack September 21 and 22, 2006 11

7 Plots of CMM data obtained at the SDA inlet on September 21 and 22, 2006.................. 12

8 Stack total Hg removal efficiencies of the various additives during December 2006 testing at HAW5 12

9 Stack total Hg removal efficiencies of the various additives during July 11 to 17, 2007, testing at HAW5 13

10 Total mercury removal efficiencies upon addition of various amounts of DARCO Hg-LH and Hg.. 14

11. Comparison of coal-based and OH mercury concentrations during baseline tests 22

12 Simplified flow schematic of MC4 23

13 Hourly average CMM-based mercury removal and CMM data at the ESP and FGD outlets.. 27

14 Plot of mercury removal efficiencies obtained at MC4 during long-term testing over a period of 1 month 27

15 M30B and CMM results obtained at the FGD outlet during the first week of long-term testing.. 28

16 M30B and CMM results obtained at the ESP FGD outlet during the first week of long-term testing.. 29

Continued…

LIST OF FIGURES (continued)

17 M30B and CMM results obtained at the FGD outlet during the last week of long-term testing 29

18 M30B and CMM results obtained at the ESP outlet during the last week of long-term testing 30

19 Mercury concentration of the liquid portions of the FGD slurry samples during baseline and long-term testing 31

20 Mercury concentration of the liquid and solid portions of the overflow slurry samples during baseline and long-term testing 31

21 Mercury concentration of the liquid and solid portions of the underflow slurry samples during baseline and long-term testing 32

LIST OF TABLES

1 Brief Descriptions of the Units Selected for the Tests 2

2 Preliminary Baseline Results Obtained Across the SDA–FF at HAW5 8

3 Summary of Results at the Stack During September 17 to 26, 2006, Testing 9

4 Summary of Results at the SDA During September 17 to 26, 2006, Testing 9

5 Summary of Results at the Stack During December 1 to 6, 2006, Testing........................... 9

6 Summary of Results at the SDA During the December 1 to 6, 2006, Testing.................... 10

7 Summary of Results at the Stack During July 11 to 17, 2007, Testing at HAW5 11

8 Summary of Results at the Stack During the November–December 17, 2007, Testing..... 13

9 Comparison of the Performances of the Various Additives Tested at HAW5.................... 15

10 Properties of Coal Samples Collected During the September Testing at HAW5 16

11 Coal Properties During the December 2–6, 2006, Testing 17

12 Coal Properties During the July 12 to 17, 2007, Testing 18

13 Coal Properties During the November 29 to December 2, 2007, Testing.......................... 19

14 Summary of the Properties of Coal Samples Collected During Testing at HAW5 20

15 Summary Mercury Content in Ash and Slurry Samples from HAW5................................ 20

16 Coal Properties During Parametric Testing at MC4, June 2007 21

17 Mill Creek Baseline Results Obtained in This Study... 21

18 Speciated Chloride and SO_3 Levels 22

19 Mercury Concentration in FGD Thickener Streams and ESP Ash Obtained During Baseline Testing.. 22

Continued…

LIST OF TABLES (continued)

20 Dust-Loading Measurements at the ESP Inlet to FGD Outlet Determined by the OH Method at Baseline 23

21 Primary Material Streams for the Mercury Mass Balance at MC4 During Baseline Sampling 23

22 Brief Descriptions of the Technologies Used for Parametric Tests Conducted at MC4 24

23 Results of Parametric Tests at MC4 Measured Across the ESP Inlet and Wet FGD Outlet Using a CMM 24

24 Mill Creek Baseline Results Obtained in a Previous Study with SCR In Service and SCR Bypassed 25

25 Vapor-Phase Mercury Concentration Measured Using Sorbent Traps Compared with CMM Measurements 25

26 Average Coal Properties During Long-Term Testing at MC4 26

27 Summary of M30B Results During Long-Term Test at MC4 28

28 Method 29 Measurements of Hg Concentrations During Long-Term Test at MC4 30

29 Mercury Concentrations in the FGD Thickener Flow Streams During the Long-Term Test at MC4 30

30 Primary Material Streams for MC4 During the Long-Term Test 32

31 Gypsum Mercury Concentrations 32

LONG-TERM DEMONSTRATION OF SORBENT ENHANCEMENT ADDITIVE TECHNOLOGY FOR MERCURY CONTROL

EXECUTIVE SUMMARY

Long-term demonstration tests of advanced sorbent enhancement additive technologies have been completed at the Louisville Gas & Electric's Mill Creek Unit 4 (MC4) located near Louisville, Kentucky, which show that mercury removal efficiencies >90% are achievable from baseline and from coal mercury levels. Prior to the long-term study, parametric tests were completed on a suite of technologies with the aim to find the best technology and optimum conditions necessary to achieve the >90% removal target on an eastern bituminous coal.

Among the several technologies tested at the MC4 station, the Babcock & Wilcox (B&W) scrubber additive, added at the rate of 80 g/hr, was found to yield mercury capture efficiency greater than 90% from both baseline level and coal levels. Hence, a decision was reached by the project team, including the U.S. Department of Energy (DOE) representatives, to use the B&W reemission additive for the long-term study. The amount of reemission from the wet flue gas desulfurization observed at MC4 was significantly lower than previously reported. Addition of powdered activated carbon (PAC) appeared to have no measurable effect on the emitted mercury concentration. In addition to continuous mercury monitor (CMM) and Ontario Hydro measurements, the U.S. Environmental Protection Agency Method 30B (sorbent trap) measurements were also obtained for comparison. There was a surprisingly close agreement between sorbent trap and CMM results, which seems to suggest that sorbent traps are potentially a cheaper, useful alternative to CMMs for making flue gas mercury concentration measurements. Detail analysis of the coal properties revealed that the moisture content was low (<10%), but chlorine and sulfur levels were high (>1100 ppm and > 3%, respectively). The nitrogen content was about 1.5% on average, and the heating value was about 12,000 Btu. These values are consistent with what is known about typical eastern bituminous coals. Because of the relatively short duration of the study compared to the plant's lifetime, not much can be concluded on the impact of Hg mass balance on the plant's operation. However, during the 1-month period of study, a significant drop in the amount of Hg in gypsum was noticed as a result of the increased Hg capture by the B&W reemission additive. Hence, the gypsum by-product, which is sold to a wall boarding company, would be considered to be of salable grade since the Hg level dropped by at least 10% compared to previous levels reported by the plant.

At Hawthorne Unit 5 (HAW5), results of the parametric tests revealed that two possible technologies are capable of achieving more than 90% mercury removal from baseline and from coal mercury levels. These include addition of PAC (2 lb/Macf) in combination with Cl_2 (500 ppm) and the Norit DARCO® Hg-LH additive (3 lb/Macf), which showed performances of 94% and 93%, respectively, from coal mercury levels and 93% and 90%, respectively, from baseline mercury levels. Furthermore, addition of PAC (322 lb/hr) in conjunction with Cl_2 (1200 ppm) and the Norit DARCO Hg-LH (2 lb/Macf) each afforded 89% removal from coal mercury levels; each of these was only about 3% short of 90% removal from baseline. Substantial selective catalytic reduction catalyst blinding was observed at the Hawthorn station, which led to lower oxidized elemental mercury levels. A limited number of sorbent trap

measurements also showed reasonable agreement with CMM data. Detail analysis of the coal samples showed a relatively high moisture content (~20%) and very low chlorine, sulfur, and nitrogen levels (~15 ppm, <0.5% and <1%, respectively). Because of the higher amount of moisture, the average heating value was about 10,000 Btu. However, these properties are within the range that can be expected for typical PRB subbituminous coals.

LONG-TERM DEMONSTRATION OF SORBENT ENHANCEMENT ADDITIVE TECHNOLOGY FOR MERCURY CONTROL

INTRODUCTION

The use of sorbent enhancement additive (SEA) technology, e.g., powder activated carbon (PAC) sorbents, for advanced control of mercury emissions is increasingly becoming one of the most promising mercury emission control options for industrial coal-fired electric utilities. The Energy & Environmental Research Center (EERC) has been developing and testing advanced mercury control technologies for power plants firing coal for the past 13 years. Projects funded by the U.S. Environmental Protection Agency (EPA) through the EERC's Center for Air Toxic Metals® (CATM®) [1–4] and those funded jointly by the industry and the U.S. Department of Energy (DOE) on lignite [5] and subbituminous coals [6], have led to greater experience in the development and testing of new SEA technologies for mercury control. Many large-scale studies involving SEAs have been conducted, which show significant improvement in mercury capture [7–9]. Recent short-term testing of SEA2 using injection Technique 2 (SEA2-T2) conducted at Antelope Valley Station and Hawthorn Unit 5 (HAW5) showed mercury capture levels greater than 90% were achievable with this technology [8].

Initial understanding of the mechanisms that have led to the development of advanced mercury control technologies was gained through CATM. The CATM studies provided a basic understanding of factors that influence the ability of mercury to react and bond with sorbents in flue gas atmospheres that are characteristic of coal-fired systems and/or coal types [1–4]. The key requirement for enhanced mercury capture through addition of SEAs is the formation of a carbon–mercury–halogen complex on the surface of the carbon [10]; SEA2 has been shown to also enhance the formation of active sites on fly ash particles [6–7]. The dominant form of Hg in coal combustion flue gas varies with the coal types; for subbituminous coals from the southern Powder River Basin (PRB) region, the elemental form of mercury is dominant, while bituminous coals have higher levels of oxidized and particulate forms of mercury [11].

Previous studies at the EERC found that the initial reactivity of PAC in the capture of elemental mercury was very low when tested on a subbituminous coal-simulated flue gas, while for bituminous coal, the initial carbon sorbent reactivity was very high [1–4]. However, early breakthrough of mercury occurs for simulated bituminous coal flue gases. This finding led to the use of SEAs to increase the reactivity of sorbents and possibly the fly ash, enabling the enhanced capture of mercury [5]. SEAs have been used in other field studies to control mercury emissions [6]. Further insights into the fundamental mechanisms of Hg bonding to sorbents have recently been published by Olson et al. [10] that support the need for SEA agents combined with PAC injection. The feasibility of the SEA2–PAC concept as well as improved methods for use of SEA2-T2 combined with PAC, has been tested recently in short-term testing at full-scale utilities [8], but long-term studies to establish the long-term reliability of these technologies are hitherto yet to be performed.

The units selected for testing in this project include the following: Kansas City Power & Light's (KCP&L) HAW5 located near Kansas City, Missouri, which has a selective catalytic reduction (SCR) system, a spray dryer absorber (SDA), and a fabric filter (FF), and Louisville Gas & Electric's (LG&E) Mill Creek Unit 4 (MC4) located near Louisville, Kentucky. The MC4 station is equipped with an SCR, an electrostatic precipitator (ESP), and a wet flue gas desulfurization (FGD) scrubber. The choice of these units was carefully made so as to provide an opportunity to test these technologies on coals with different characteristics or properties. HAW5 burns subbituminous coals, which have the predominant form of mercury as elemental, and MC4 burns eastern bituminous coals, which have higher levels of oxidized and particulate forms of mercury. Brief descriptions of these plants are given in Table 1. This project focused on determining the impact of SEA injection on the capability of PAC sorbents and entrained ash particles used to oxidize and/or remove mercury from coal combustion flue gases on a long-term basis. Previous short-term studies have shown that SEA represents a cost-effective mercury control technology with greater than 90% reduction from baseline, but the long-term reliability of this technology has not been demonstrated. The major technologies tested include SEAs, PAC, Babcock & Wilcox) B&W reemission additive and suitable combinations of these additives in various proportions. In all test cases, a baseline mercury removal level was established, followed by a suite of parametric tests aimed at determining the optimum conditions for achieving >90% Hg removal from baseline and for what technology. The best technology that yielded >90% Hg removal was then used in the long-term studies to determine its reliability on a long-term basis. The speciated mercury concentrations in the flue gases were determined in each system using the Ontario Hydro (OH) wet chemical sampling method and continuous mercury monitors (CMMs) at both sites. At the end of parametric tests at the MC4 station, the B&W reemission additive was found to yield >90% removal at an add rate of 80 g/hr and so was tested further for 1 month. After the parametric tests at the HAW5 station, it was found that two technologies were capable of achieving >90% Hg removal: addition of PAC (2 lb/Macf) in combination with Cl_2 (500 ppm) showed the highest performance of 94% removal from coal and 93% from baseline, while the Norit DARCO® Hg-LH additive (3 lb/Macf) comes close at 93% removal from coal and essentially 90% from baseline.

The results of this study demonstrate the usefulness of the tested technologies in achieving >90% Hg removal from baseline and/or from coal levels and are expected to be applicable to most utilities that burn subbituminous and bituminous coals in the United States and Canada. The processes tested here have also been previously proven at the pilot scale and in full-scale tests with lignite, PRB, and blended PRB–bituminous coals. Data from additional optimization tests and the 1-month study at the MC4 station showed no foreseeable problems with long-term field applications.

Table 1. Brief Descriptions of the Units Selected for the Tests

Owner, Unit	Coal Type	Boiler Type, size	Particulate Control	SO_2 Control	NO_x Control
KCP&L, HAW5	PRB subbituminous	Wall-fired, 550 MW	FF	SDA	LNB,[a] OFA,[b] SCR
LG&E, MC4	Eastern bituminous	Wall-fired, 530 MW	ESP/SCR = 232	Wet FGD	LNB, SCR

[a] Low NO_x burner.

[b] Overfire air.

This report is organized such that a description of the methods is given in Section II, the results are presented and discussed in Section III, and final conclusions to the study are given in Section IV.

METHODS

Large-scale long-term demonstration tests were carried out at two power plants, the LG&E MC4 power station in Kentucky and the KCP&L HAW5 station, to further illustrate the capabilities of SEA injection with PAC as a cost-effective mercury control technology with >90% reduction levels. Prior to the large-scale studies, parametric tests were performed to obtain optimum conditions for the injection of SEAs and/or PACs. Measurements of mercury speciation in the flue gases were made using two techniques: the OH method and CMMs. The OH method procedures adopted are those prescribed by ASTM International (D6784-02), and the CMMs and conversion systems recently purchased by the EERC are manufactured by PS Analytical (Sir Galahad), Tekran, Semtech, and Horiba. Additional analyses were carried out on coal and ash samples. The locations of SEA and/or PAC injection and sampling points for the coal, ash, and flue gases are shown in Figures 1 and 2.

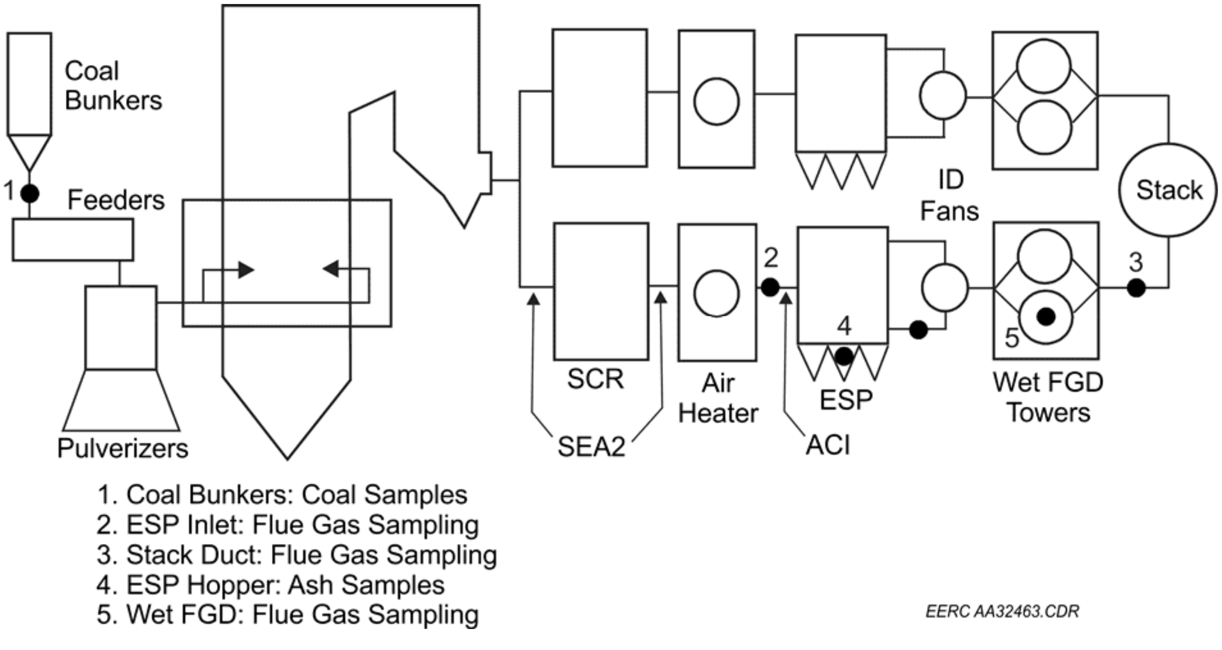


Figure 1. Schematic of MC4 showing SEA/PAC injection points and sampling locations (ACL is activated carbon injection; ID is induced draft).

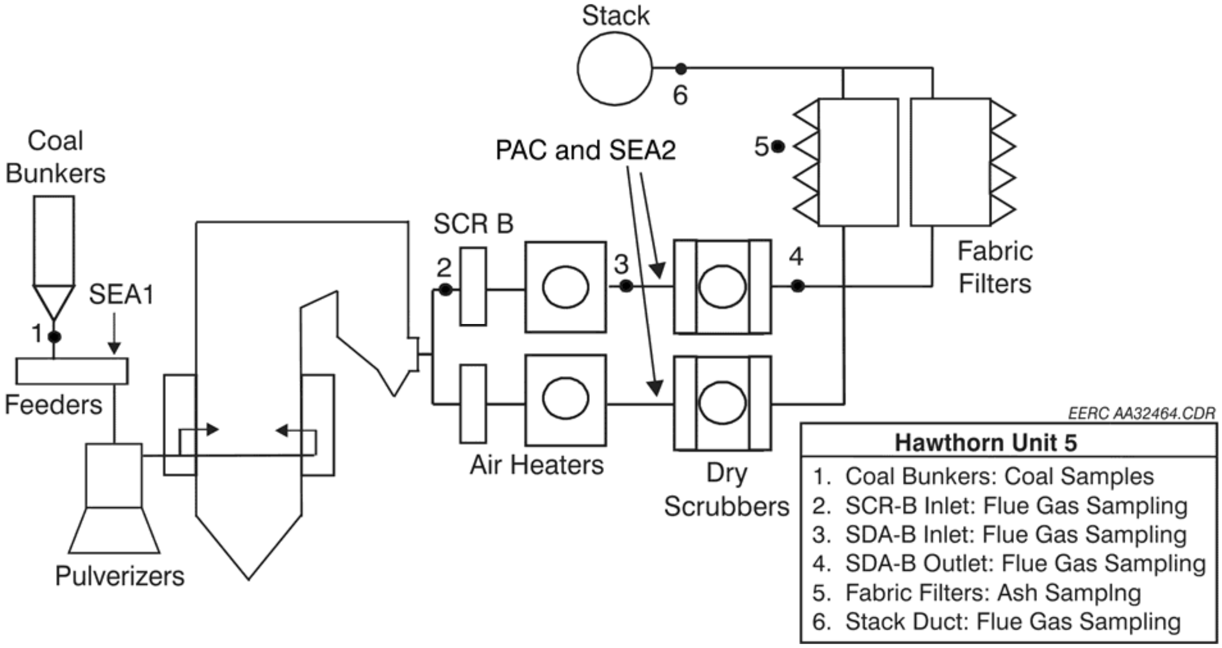


Figure 2. Schematic of HAW5 showing SEA/PAC injection points and sampling locations.

The Ontario Hydro Method

The OH method is a technique used for the measurement of particle-bound, oxidized, elemental, and total mercury in stationary-source flue gases according to standard procedures prescribed by ASTM [12]. It provides data that can be used more generally for dispersion modeling, deposition evaluation, human health and environmental impact assessments, emission reporting, and compliance determinations. Particle-bound, oxidized, and elemental mercury measurements before and after control devices may be necessary for optimizing and evaluating the mercury removal efficiency of emission control technologies. At HAW5, the OH method was performed at the SDA inlet and at the stack, while at MC4, it was carried out at the ESP inlet and at the stack. As a validation of the accuracy of the method, the error tolerances in sample measurements were required to be <10% of sample value or 10 times the detection limit of equipment, <25% of sample value for field blanks, <15% of true value for field and laboratory spikes, and <10% for precision; all measurements were also required to be 100% complete in order to be considered.

To ensure the accuracy of the measurements, one field blank and one field spike were collected at each sample location per test condition and evaluated during the initial baseline and parametric testing. Following this period, OH sampling was done three more times during the remainder of the long-term testing. Field blanks and spikes were analyzed at each sampling location for each sampling period. The field blanks and spikes consisted of sample trains that were assembled and taken to the same location as a test sample, leak-checked, and recovered. If the field blanks did not meet the validation criteria, the data were flagged, and corrective actions were taken to determine the source of the contamination, which was possible because the analyses of blanks and field spikes were performed on-site.

Continuous Mercury Monitors

The CMM technique is relatively new and was adopted in 2005 by EPA as part of the mercury rule-making process for coal-fired power plants. EPA established a program for monitor certification and quality assurance/quality control (QA/QC) under 40 CFR, Part 60 and Part 75. At HAW5, CMM sampling took place at the SDA inlet and at the stack, while at MC4, CMM sampling was done at the ESP and at the stack.

In addition to having qualified personnel to operate the CMMs for this project, the EERC followed the QA/QC guidelines in Part 75, including daily calibrations. Normally, calibration is done by first sampling zero gas (air that has passed through a carbon trap), followed by injecting an exact amount of primary standard mercury vapor into the instrument. These procedures are done four times to determine the type of scatter. In addition, the internal EERC QA/QC standard is that $R^2 = 0.999$. If this standard is not met, additional calibration is completed or more substantial maintenance of the instrument is done, which includes cleaning all lines, checking filters, etc.

Parametric Test Descriptions

Parametric tests were conducted at both plants in an effort to determine the optimum conditions necessary for the long-term studies. As a general procedure, site visits were conducted and followed by installation of the injection equipment for SEAs and PAC as well as the CMMs at appropriate locations. Once the CMMs were installed and tested, baseline measurement of mercury levels and species was determined and validated using the OH method. Upon completion of baseline tests, 2 weeks of parametric tests at MC4 (3 weeks in the case of HAW5) were conducted to determine the optimum concentrations of SEAs and PAC required to achieve the objective of >90% control above the baseline mercury capture level. Several test runs were conducted involving injection of SEAs (SEA1, SEA2 and SEA2-T2) alone or in combination with PAC, depending upon what choice meets the project objective of >90% reduction level.

PAC Injection System

The dry PAC injection system was a portable Norit Americas, Inc., PORTA-PAC® unit, which pneumatically conveys a predetermined and adjustable amount of PAC from super sacks (about 900 lb) into the flue gas stream. A volumetric feeder delivers PAC into a pneumatic conveyor where a high-velocity airstream transfers the PAC to the injection point. Feeder operation is controlled with a series of interlocks, which allow local and/or remote operation and monitoring of the system. A schematic of the injection system is shown in Figure 3. The injection duct had a diverging cross-sectional area in the direction of flow, and there were a series of turning vanes to distribute the flow of gas. Fluid flow modeling was performed to determine the appropriate number and location of PAC injection points. Modeling results of the as-tested setup are shown in Figure 4 and indicate good PAC distribution entering the ESP.

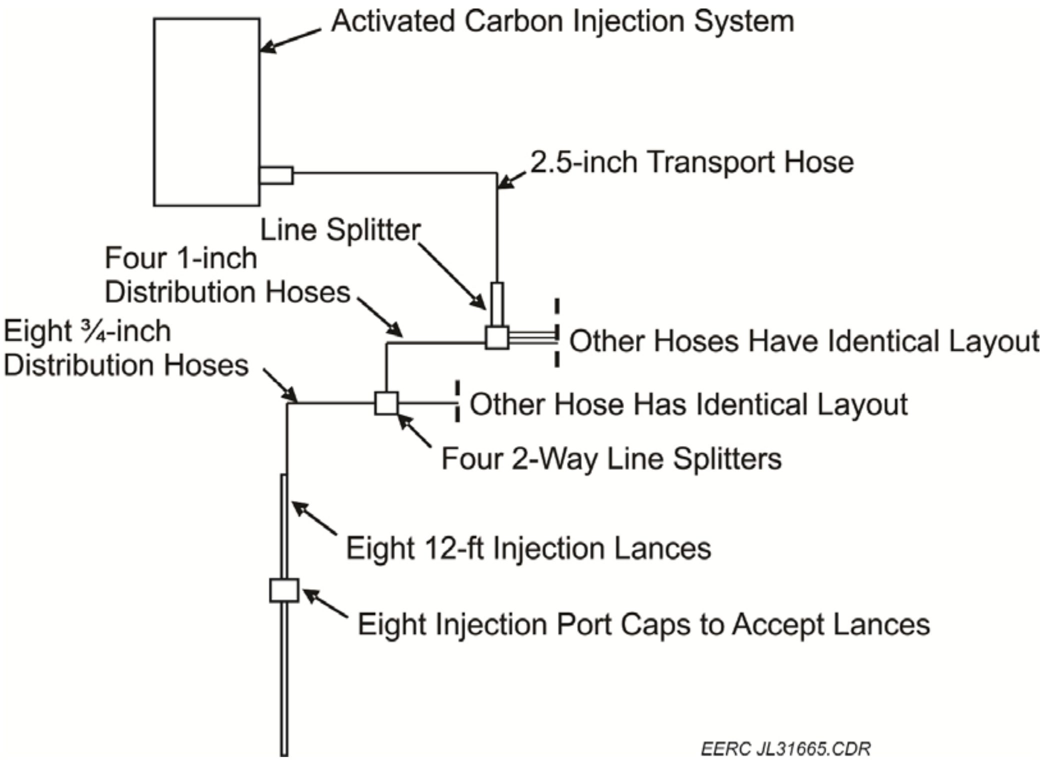


Figure 3. Schematic of ACI system.

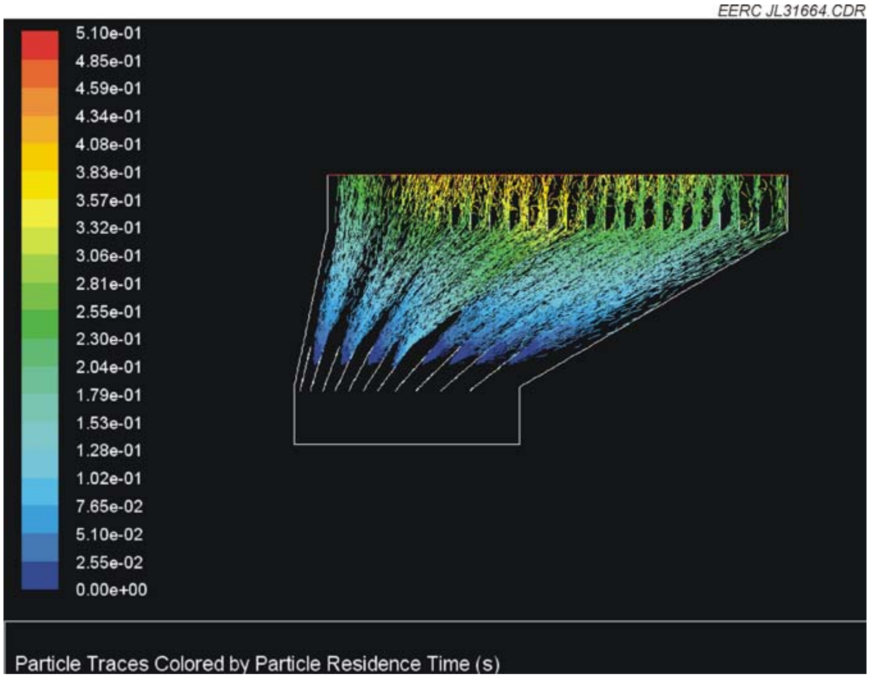


Figure 4. Simulated fluid flow distribution for an ACI system.

SEA Injection Systems

A SEA injection system was designed for adding SEAs, sometimes in combination with PAC, at the selected locations at both plants. The basic operational process of the SEA injection system is that a solid material is fed to a furnace, where it is vaporized and the gas is then injected directly into the flue gas ducts of the plant or can be added with PAC. These furnaces were initially intended to fire natural gas and then mix the gas products with PAC prior to injection into the gas duct. Since SEA2 was to be added upstream and downstream of a particular control device, it was required that these skids be located close to the injection location. Consequently, a natural gas furnace was determined to be too bulky and complex to be installed on the decking next to the injection point. As a result, the natural gas furnace was replaced with an electrical furnace.

The B&W reemission additive injection skid was supplied by the B&W Corporation. The injection skid, which was mounted on a trailer, consisted of a feed pump, recirculation spray, and the necessary controls to continuously pump and direct liquid out of a storage tank (in a tanker truck located near the injection skid) into the FGD system.

Long-Term Demonstration Test Descriptions

Long-term demonstration tests were performed following the end of parametric tests for a period of 1 month at MC4. At the MC4 test site, the decision to proceed with the long-term studies was contingent on whether the parametric tests yielded >90% reduction levels; an indication of <90% removal level would bring the long-term studies to a halt. The optimum ratio of SEA and PAC (if required) was determined from the parametric tests, and a 1-month long-term test was done with the SCR in service at MC4. In addition to determining the long-term viability of injecting SEA (and potentially PAC), the balance-of-plant impacts were evaluated. During the long-term tests, the mercury removal levels were based primarily on the coal mercury content and a CMM located at the stack. However, three times during the 1-month period at MC4, additional measurements using the OH method were completed.

Coal, Ash, and Slurry Analyses

Coal, ash, limestone, gypsum, and FGD slurry samples were collected by plant personnel in accordance with established plant protocols and returned to the EERC for analysis. The coal samples were analyzed for Hg and Cl_2 content, proximate and ultimate properties, and its heating value, using standard ASTM International methods. Proximate and ultimate analyses were conducted using ASTM Methods D3172, D5142, and D3176, while chlorine was analyzed following ASTM Method D6721-01 (Standard Test Method for Determination of Chlorine in Coal by Oxidative Hydrolysis Microcoulometry) using a Mitsubishi Model TOX-100 total chlorine analyzer. Coal Hg contents were determined using a heated acid extraction followed by cold-vapor atomic absorption spectroscopy according to ASTM D6414 (Standard Test Methods for Total Mercury in Coal and Coal Combustion Residues by Acid Extraction or Wet Oxidation/Cold Vapor Atomic Absorption). Particle-bound Hg in ESP ash was determined using ASTM D6414 and loss on ignition (LOI) using standard ASTM methods at the EERC.

Limestone, gypsum, and FGD slurry solids were analyzed for mercury content according to ASTM D6414 and the FGD slurry liquid fractions were analyzed using EPA SW-846 7470A.

RESULTS AND DISCUSSION

The EERC has successfully completed a large-scale demonstration study of an improved cost-effective mercury control technology capable of achieving >90% mercury removal from baseline. This technology is based on the injection of SEAs and/or PAC into the combustion flue gas streams. A long-term demonstration and a series of short-term parametric tests were carried out at LG&E's MC4 power station in Kentucky. Both units have wall-fired boilers. HAW5, a 550-MW facility, burns subbituminous coal from PRB, while MC4 burns eastern bituminous coal and has a boiler size of 530 MW. Optimized conditions for the injection of SEAs and/or PAC were determined from parametric tests that were performed prior to the long-term study at the MC4 station. Although long-term studies were not performed at HAW5, optimal conditions for achieving >90% mercury removal from baseline level were determined based on the results of the parametric tests.

The main technologies tested at HAW5 include injection of various amounts of Cl_2 (SEA1), SEA2, PAC, DARCO Hg-LH and DARCO Hg into the flue gas streams. Mercury levels at baseline and during sorbent injection were measured using CMMs, OH method, and occasionally EPA Method 29. Data were collected at two test locations: the SDA inlet and at the stack during the September 17–26 and December 1–6, 2006, test periods. Preliminary baseline tests were carried out on September 18 and 19, 2006, and these results are presented in Table 2, while results of additional baseline and addition of SEAs are given in Tables 3–6 and Figures 5–8. In subsequent test rounds, i.e., July 11–17 and November 29 to December 2, 2007, measurements were only made at the stack because the SDA location was determined to be very challenging and the data obtained at the SDA were rather too noisy and not very meaningful or reliable. These results are presented in Tables 7 and 8 and Figures 9 and 10. The performance of all additives tested and their proportions are compared in Table 9.

Results from the analysis of coal samples are given in Tables 10–13 and a succinct summary is given in Table 14, while Hg measurements from the analysis of ash samples are presented in Table 15.

Table 2. Preliminary Baseline Results Obtained Across the SDA–FF at HAW5. Percent Hg Removals Are Based on Coal Inlet and CMM or OH Outlet Values

Date	Coal Inlet, $\mu g/Nm^3$	CMM Inlet, $\mu g/Nm^3$	CMM Outlet, $\mu g/Nm^3$	OH Inlet, $\mu g/Nm^3$	OH Outlet, $\mu g/Nm^3$	Mercury Removal, %	
						OH	CMM
09/18/06	13.67	7.23	8.7	14.28	11.37	16.8	36.4
09/18/06	13.67	7.52	8.64	13.61	10.86	20.6	36.8
09/19/06	12.82	6.24	8.28	11.27	10.54	17.8	35.4
09/19/06	12.82	6.93	8.64	12.67	10.78	15.9	32.6

Table 3. Summary of Results at the Stack During September 17 to 26, 2006, Testing. Mercury Values Are Calculated on a Dry Basis at 3% Oxygen

			Percent Total Hg Removal	
Test	Total Hg, μg/Nm^3	Elemental Hg, μg/Nm^3	From Baseline	From Coal
Baseline (CMM)	8.905	8.043	-	31.9
Baseline (OH)	10.9	10.68	-	16.7
Cl_2 600 ppm	3.949	3.228	55.6	69.8
Cl_2 800 ppm	3.532	2.960	60.3	73.0
PAC 1 lb/Macf	5.364	5.358	39.8	59.0
PAC 1 lb/Macf and SEA2 2 lb/hr	4.310	4.085	51.6	67.0
PAC 1 lb/Macf and SEA2 6 lb/hr	4.588	4.447	48.5	64.9
PAC 3 lb/Macf and SEA2 18 lb/hr	1.851	1.774	79.2	85.8

Table 4. Summary of Results at the SDA (inlet) During September 17 to 26, 2006, Testing. Mercury Values Are Calculated on a Dry Basis at 3% Oxygen

			Percent Hg Removal	
Test	Total Hg, μg/Nm^3	Elemental Hg, μg/Nm^3	From Baseline	From Coal
Baseline (CMM)	9.563	8.076	-	26.9
Baseline (OH)	10.87	7.05	-	16.9
Cl_2 600 ppm	14.831	8.389	-55.1[‡]	-13.4
Cl_2 800 ppm	12.075	5.469	-26.3[‡]	7.7
Cl_2 1000 ppm	10.188	5.862	-6.5[‡]	22.1

Table 5. Summary of Results at the Stack During December 1 to 6, 2006, Testing. Mercury Values Are Calculated on a Dry Basis at 3% Oxygen

			Mercury Removal, %	
Test	Total Hg, μg/Nm^3	Elemental Hg, μg/Nm^3	From Baseline	From Coal
Baseline (CMM)	8.764	7.986	–	21.9
OH (during sorbent testing)	1.175	1.15	–	89.5
PAC 3.3 lb/Macf	5.881	5.130	32.9	47.6
PAC 3.3 lb/Macf and Cl_2 800 ppm	4.222	2.700	51.8	62.4
PAC 3.3 lb/Macf and Cl_2 1000 ppm	3.681	2.172	58.0	67.2
PAC 3.6 lb/Macf and Cl_2 1000 ppm	2.612	1.800	70.2	76.7
PAC 3.6 lb/Macf and $Cl_2$1200 ppm	1.635	0.999	81.4	85.4
Cl_2 1200 ppm	3.230	2.021	63.1	71.2
PAC 3.3 lb/Macf and SEA2	2.719	2.767	69.0	75.8
PAC 300 lb/hr and SEA2	2.440	2.725	72.2	78.3
PAC 300 lb/hr	3.425	2.910	60.9	69.5
PAC 322 lb/hr and Cl_2 1200 ppm	1.198	0.662	86.3	89.3
PAC 420 lb/hr and Cl_2 1200 ppm	1.311	0.746	85.0	88.3

Table 6. Summary of Results at the SDA (inlet) During the December 1 to 6, 2006, Testing. Mercury Values Are Calculated on a Dry Basis at 3% Oxygen

			Percent Total Hg Removal	
Test	Total Hg, µg/Nm^3	Elemental Hg, µg/Nm^3	From Baseline	From Coal
Baseline (CMM)	10.214	9.382	–	9.0
Baseline (OH)	11.8	10.1	–	−5.2
PAC 3.3 lb/Macf	5.694	5.129	44.3	49.3
PAC 3.3 lb/Macf and Cl_2 800 ppm	9.294	7.066	9.0	17.2
PAC 3.3 lb/Macf and Cl_2 1000 ppm	10.635	8.073	−4.1	5.3
PAC 3.6 lb/Macf and Cl_2 1200 ppm	11.574	6.273	−13.3	−3.2
PAC 3.9 lb/Macf and Cl_2 1200 ppm	4.311	4.054	57.8	61.6
Cl_2 1200 ppm	8.448	4.850	17.3	24.7
PAC 3 lb/Macf	15.862	9.210	−55.3	−41.4

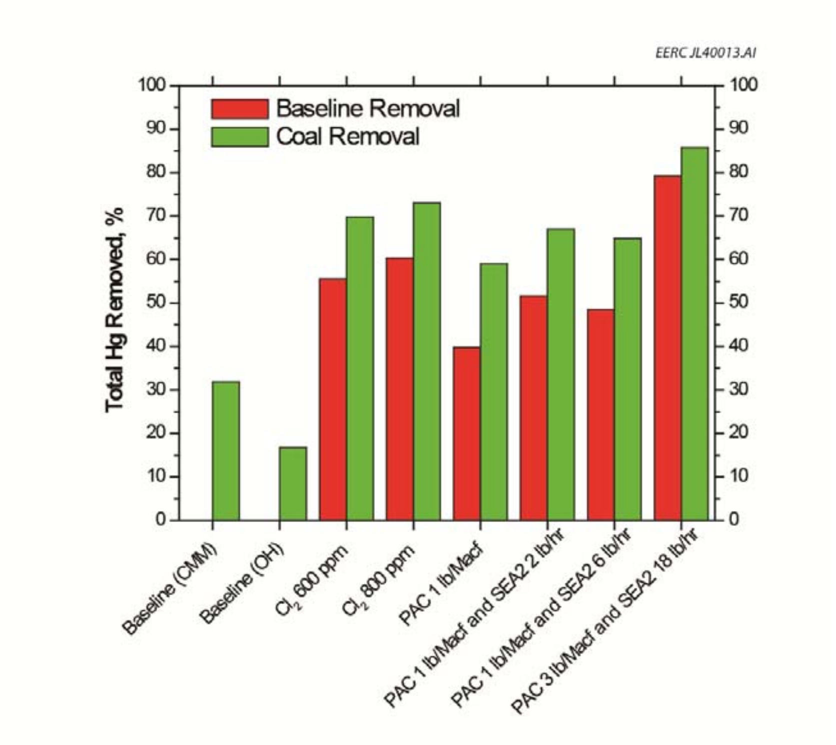


Figure 5. Stack total Hg removal efficiencies of the various additives during September 2006 testing at HAW5.

EERC JL40019.AI

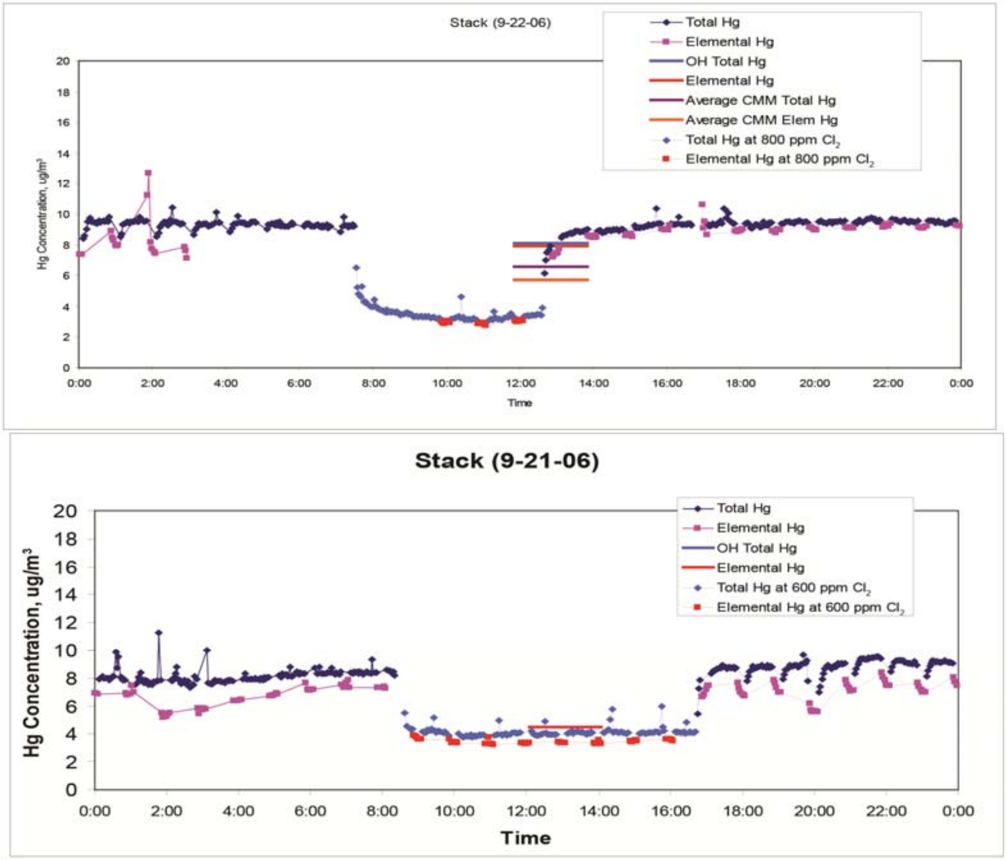


Figure 6. Plot of CMM data obtained at stack September 21 and 22, 2006.

Table 7. Summary of Results at the Stack During July 11 to 17, 2007, Testing at HAW5. Mercury Values Are Calculated on a Dry Basis at 3% Oxygen

Test	Total Hg, µg/Nm^3	Elemental Hg, µg/Nm^3	Percent Hg Removal From Baseline	Percent Hg Removal From Coal
Baseline (CMM)	6.483	6.020	–	17.5
Baseline (OH)	7.1	6.8	–	9.7
Cl_2 600 ppm	2.144	1.340	66.9	72.7
Cl_2 800 ppm	1.564	0.999	75.9	80.1
Cl_2 1000 ppm	1.816	1.003	72.0	76.9
$Cl_2$1200 ppm	1.593	1.060	75.4	79.7
Cl_2 250 ppm and PAC 2 lb/Macf	0.930	0.850	85.7	88.2
Cl_2 500 ppm and PAC 2 lb/Macf	0.475	0.425	92.7	94.0

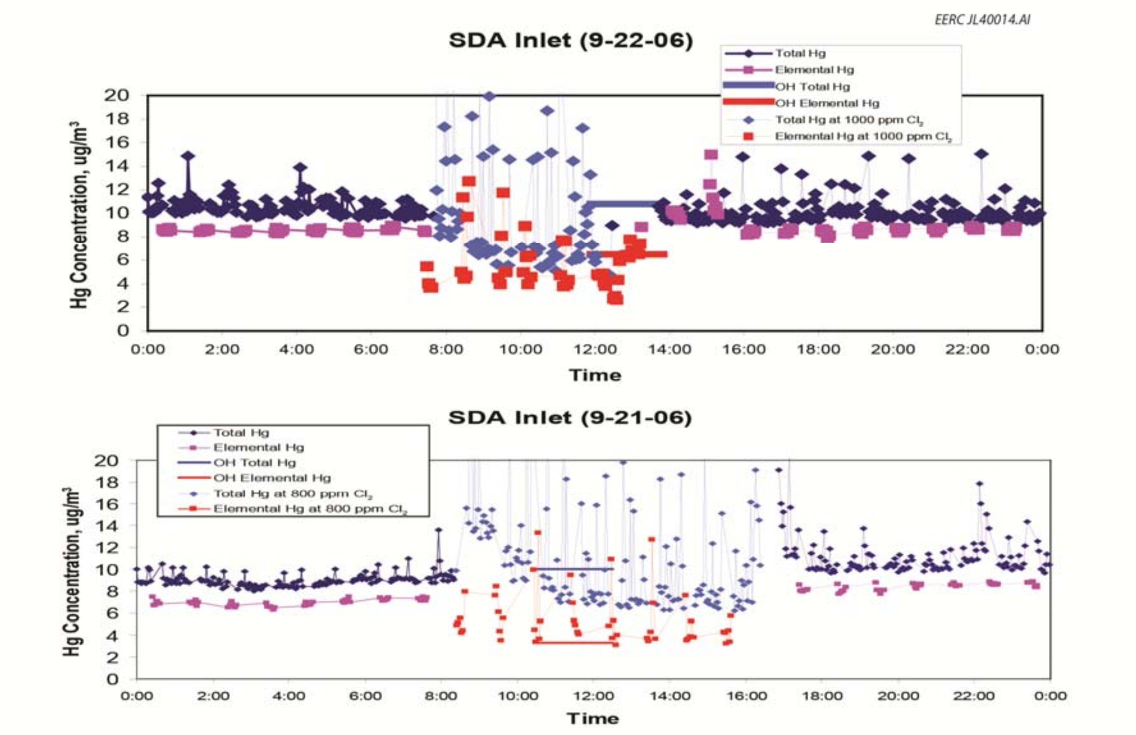


Figure 7. Plots of CMM data obtained at the SDA inlet on September 21 and 22, 2006.

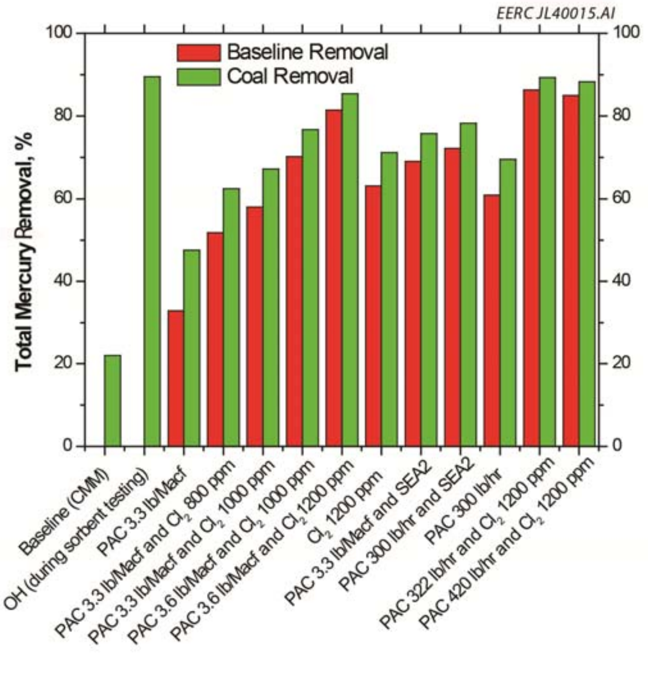


Figure 8. Stack total Hg removal efficiencies of the various additives during December 2006 testing at HAW5.

Table 8. Summary of Results at the Stack During the November–December 17, 2007, Testing. Mercury Values Are Calculated on a Dry Basis at 3% Oxygen

Test	Total Hg, µg/Nm^3	Elemental Hg, µg/Nm^3	Percent Total Hg Removal	
			From Baseline	From Coal
Baseline (CMM)	6.417	6.464	–	33.3
Baseline (OH)	7.4	7.2	–	23.2
DARCO Hg-LH 1 lb/Macf	2.640	3.332	58.9	72.6
DARCO Hg-LH 2 lb/Macf	1.047	1.201	83.7	89.1
DARCO Hg-LH 3 lb/Macf	0.660	0.690	89.7	93.1
DARCO Hg 1 lb/Macf	2.536	3.021	60.5	73.7
DARCO Hg 2 lb/Macf	1.798	1.816	72.0	81.3
DARCO Hg 3 lb/Macf	2.419	3.576	62.3	74.9
DARCO Hg 2 lb/Macf via HTD skid	1.984	2.250	69.1	79.4

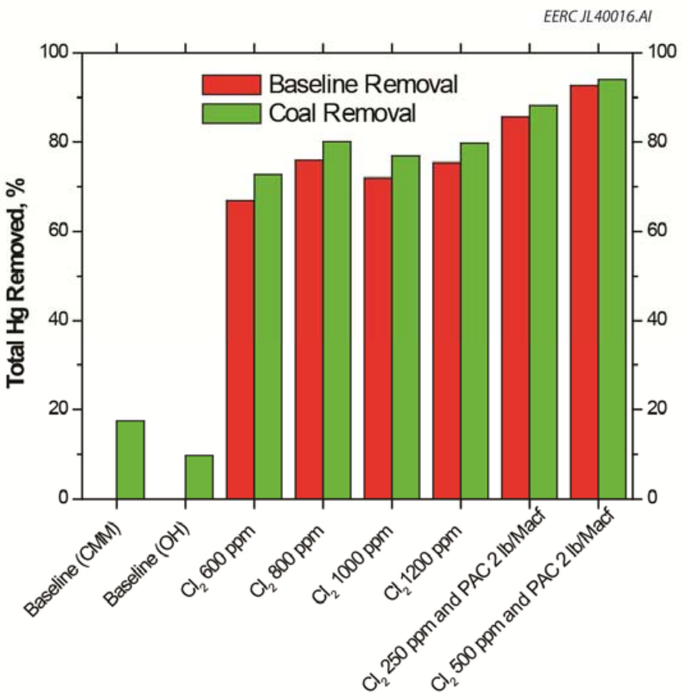


Figure 9. Stack total Hg removal efficiencies of the various additives during July 11 to 17, 2007, testing at HAW5.

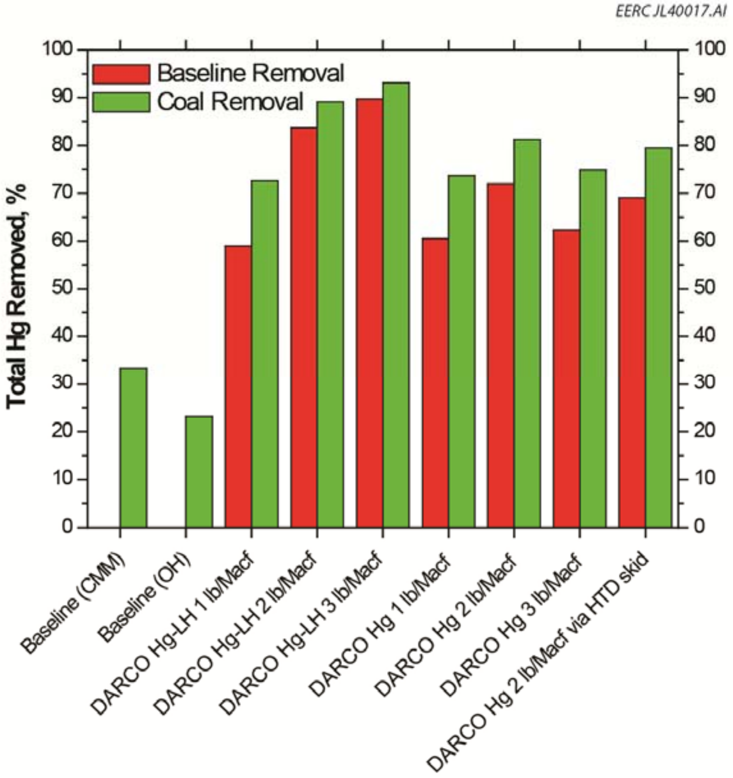


Figure 10. Total mercury removal efficiencies upon addition of various amounts of DARCO Hg-LH and Hg.

At the MC4 station, the primary technologies tested were SEA2-T2, PAC, scrubber additives, and various combinations and proportions. Mercury levels at baseline and during sorbent injection were measured using CMMs, OH method, and occasionally EPA Method 29. Coal properties determined during baseline testing are given in Table 16. Baseline CMM and OH results are presented in Table 17 and depicted graphically in Figure 11. Speciated chloride and SO_3 levels as well as Hg levels in the FGD thickener streams were also measured during baseline testing, and these results are presented in Tables 18 and 19, respectively. Dust loading on the SDA–FF was determined (see Table 20), and the primary material streams used in carrying out a baseline Hg mass balance are shown schematically in Figure 12. The calculated process stream parameters are given in Table 21. Descriptions of the tests conducted at MC4 are summarized in Table 22 and parametric test results are summarized in Table 23. Results obtained from a previous study at MC4 with the SCR in service and with the SCR bypassed are also shown in Table 24 for comparison with those obtained in this study. EPA Method 30B (sorbent traps) tests were performed during the short-term baseline test period, and the results are given in Table 25.

Table 9. Comparison of the Performances of the Various Additives Tested at HAW5

	Percent Total Hg Removal	
Additive	From Baseline	From Coal
Cl_2 600 ppm	66.9	72.7
Cl_2 800 ppm	75.9	80.1
Cl_2 1000 ppm	72.0	76.9
Cl_2 1200 ppm	75.4	79.7
PAC 1 lb/Macf	39.8	59.0
PAC 3.3 lb/Macf	32.9	47.6
PAC 300 lb/hr	60.9	69.5
PAC 2 lb/Macf and Cl_2 250 ppm	85.7	88.2
PAC 2 lb/Macf and Cl_2 500 ppm	92.7	94.0
PAC 3.3 lb/Macf and Cl_2 800 ppm	51.8	62.4
PAC 3.3 lb/Macf and Cl_2 1000 ppm	58.0	67.2
PAC 3.6 lb/Macf and Cl_2 1000 ppm	70.2	76.7
PAC 3.6 lb/Macf and Cl_2 1200 ppm	81.4	85.4
PAC 322 lb/hr and Cl_2 1200 ppm	86.3	89.3
PAC 420 lb/hr and Cl_2 1200 ppm	85.0	88.3
PAC 3.3 lb/Macf and SEA2	69.0	75.8
PAC 300 lb/hr and SEA2	72.2	78.3
PAC 1 lb/Macf and SEA2 2 lb/hr	51.6	67.0
PAC 1 lb/Macf and SEA2 6 lb/hr	48.5	64.9
PAC 3 lb/Macf and SEA2 18 lb/hr	79.2	85.8
DARCO Hg-LH 1 lb/Macf	58.9	72.6
DARCO Hg-LH 2 lb/Macf	83.7	89.1
DARCO Hg-LH 3 lb/Macf	89.7	93.1
DARCO Hg 1 lb/Macf	60.5	73.7
DARCO Hg 2 lb/Macf	72.0	81.3
DARCO Hg 3 lb/Macf	62.3	74.9
DARCO Hg 2 lb/Macf via HTD skid	69.1	79.4

Similar tests were conducted during the long-term study as were done for the baseline. The coal properties over the long term are summarized in Table 26. Hourly averages of the CMM and OH data over the long-term at the ESP and FGD are presented in Figure 13 and Hg removal efficiencies are shown graphically in Figure 14. Long-term sorbent trap test results are given in Table 27; those obtained in the first and last week of the long-term tests are plotted in Figures 15–18. Mercury concentrations determined by EPA Method 29 (M29) are presented in Table 28, and concentrations found in the FGD thickener streams over the long-term period are given in Table 29. A slight modification of the filtering procedure of the thickener stream samples to include filtration at the test site as opposed to bringing them to the EERC was made; plots of the Hg concentration in these "field-filtered" samples are shown in Figures 19–21. Finally, long-term Hg mass balance determinations for the major process streams are given in Table 30, while gypsum Hg concentrations are presented in Table 31. The results obtained using CMMs are strikingly similar to those obtained using sorbent traps, which seems to suggest that sorbent traps may be a promising cheaper alternative to CMMs.

Table 10. Properties of Coal Samples Collected During the September Testing at HAW5

Property, unit	9/18/06 Average	9/19/06 Average	9/20/06 Average	Overall Average	Standard Deviation
Mercury,[a] ppm	0.114	0.106	0.105	0.108	0.0049
Chlorine,[a] ppm	10.3	11.5	20.7	14.2	6
Proximate Analysis					
Moisture, wt%	19.10	20.6	20.9	20.20	0.9644
Volatile Matter, wt%	34.86	34.22	34.14	34.41	0.3946
Fixed Carbon, wt%	40.66	40	39.75	40.14	0.4701
Ash, wt%	5.38	5.18	5.21	5.26	0.1079
Ultimate Analysis					
Hydrogen, wt%	6.12	6.1	6.1	6.11	0.0115
Carbon, wt%	55.17	54.06	53.6	54.28	0.8071
Nitrogen, wt%	1.05	0.97	0.96	0.99	0.0493
Sulfur, wt%	0.45	0.38	0.5	0.44	0.0603
Oxygen, wt%	31.83	33.32	33.62	32.92	0.9587
Heating Value, Btu/lb	9613	10942	9365	9973	848
Calculated Parameters					
F_d, dscf/MMBtu	9636	8238	9542	9139	781
Sulfur,[a] wt%	0.56	0.48	0.63	0.56	0.0751
Heating Value,[a] Btu/lb	11,883	13,781	11,839	12,501	1109
Hg,[b] µg/Nm^3	13.67	12.82	12.76	13.08	0.5090
Hg,[b] lb/TBtu	9.59	7.69	8.87	8.72	0.9592

[a] Dry basis.
[b] Flue gas basis.

These results are presented and discussed in detail below, beginning with those obtained from the HAW5 station and followed by those from the MC4 station. The presentation of results from HAW5 is such that baseline and parametric tests results are discussed simultaneously, while in the case of MC4, the baseline, parametric, and long-term test results are discussed separately.

Hawthorn Unit 5

Baseline and parametric tests were conducted at HAW5 during four different trips that began in September of 2006 and ended in December of 2007. The 2006 test trips were made September 17–26 and December 2–6 of 2006, while trips taken in 2007 were made July 12–17 and November 29 to December 30 of 2007. The main technologies tested include injection of various amounts of Cl_2 (SEA1), SEA2, PAC, DARCO Hg-LH and DARCO Hg into the flue gas streams. Mercury levels at baseline and during sorbent injection were measured using CMMs, the OH method, and occasionally EPA Method 29. Testing was done at the SDA inlet and at the stack during the September 17–26 and December 1–6, 2006, test periods. The OH method was used throughout the test period at Hawthorn Station to measure the concentrations of Hg species entering and exiting the SDA–FF as well as to evaluate the quality of CMM measurements of

Table 11. Coal Properties During the December 2–6, 2006, Testing

Property	12/03/06 Average	12/04/06 Average	12/05/06 Average	12/06/06 Average	Overall Average	Standard Deviation
Mercury,[a] ppm	0.0901	0.0961	0.0874	0.0978	0.0929	0.0049
Chlorine,[a] ppm	19.7	12	12	21.3	16.3	5
Proximate Analysis						
Moisture, wt%	20.03	20.8	21.2	20.93	20.74	0.5018
Volatile Matter, wt%	33.4	32.86	33.31	35.10	33.67	0.9838
Fixed Carbon, wt%	41.09	40.86	40.26	38.93	40.29	0.9687
Ash, wt%	5.47	5.48	5.24	5.04	5.31	0.2100
Ultimate Analysis						
Hydrogen, wt%	6.04	6.06	6.15	6.15	6.10	0.0583
Carbon, wt%	54.49	53.87	53.66	53.93	54.00	0.3544
Nitrogen, wt%	0.97	0.97	0.96	0.98	0.97	0.0082
Sulfur, wt%	0.34	0.35	0.37	0.36	0.36	0.0129
Oxygen, wt%	32.69	33.29	33.64	33.54	33.29	0.4262
Heating Value, Btu/lb	9352	9383	9322	9288	9336	41
Calculated Parameters						
F_d, dscf/MMBtu	9713	9560	9607	9691	9643	72
Sulfur,[a] wt%	0.43	0.44	0.47	0.46	0.45	0.0183
Heating Value,[a] Btu/lb	11694	11847	11830	11747	11780	72
Hg,[b] $\mu g/Nm^3$	10.89	11.65	10.56	11.79	11.22	0.5928
Hg,[b] lb/TBtu	7.70	8.11	7.39	8.33	7.88	0.4195

[a] Dry basis.

[b] Flue gas basis.

gaseous Hg. The OH method is advantageous to distinguish the effects of SEA addition and PAC injection on the speciation of elemental mercury (Hg^0), oxidized mercury (Hg^{2+}), and particulate-bound mercury ($Hg_{[p]}$) capture. However, in order to determine these effects, it was necessary to establish a baseline average and evaluate the variability in Hg species distributions for the subbituminous coal combustion flue gas.

Preliminary baseline OH method measurements at the SDA–FF outlet indicated very low $Hg_{(p)}$ and Hg^{2+} concentrations of <1 $\mu g/Nm^3$ and the dominance of Hg^0 concentration of about 10.7 ± 0.1 $\mu g/Nm^3$ (see Table 2). The average SDA inlet baseline total Hg concentration from OH method testing was 13.0 ± 1.3 $\mu g/Nm^3$. Baseline FF outlet OH average total Hg concentration was 10.9 ± 0.3 $\mu g/Nm^3$ for an inherent fly ash capture of 16%. The inlet total Hg concentrations are consistent with most PRB coals that have been tested. The percent difference between the OH method results at the SDA inlet location and the baseline average coal-derived value (13.24 ± 0.60 $\mu g/Nm^3$) was 2%. A t-test proved these two values to be statistically the same. Hence, the coal-based inlet Hg concentration values were used for determining total Hg removal efficiencies because they are a more conservative estimate of inlet Hg concentration than either OH method or CMM results.

Table 12. Coal Properties During the July 12 to 17, 2007, Testing

Property	7/12/07 Average	7/13/07 Average	7/14/07 Average	7/15/07 Average	7/16/07 Average	7/17/07 Average	Overall Average	Standard Deviation
Mercury,[a] ppm	0.0766	0.0765	0.0735	0.0984	0.0693	0.0980	0.0821	0.0128
Chlorine,[a] ppm	14	13	20	13	9	10	13	4
Proximate Analysis								
Moisture, wt%	20	20.6	19	18.5	16.9	20.5	19.25	1.4209
Volatile Matter, wt%	32.94	32.79	33.98	34.12	34.43	33.87	33.69	0.6666
Fixed Carbon, wt%	41.92	41.31	41.67	41.15	42.84	39.72	41.44	1.0298
Ash, wt%	5.14	5.3	5.35	6.23	5.83	5.91	5.63	0.4256
Ultimate Analysis								
Hydrogen, wt%	5.39	5.67	5.67	5.91	4.85	5.45	5.49	0.3640
Carbon, wt%	68.23	68.43	67.86	67.34	68.32	68.54	68.12	0.4473
Nitrogen, wt%	0.71	0.73	0.63	0.65	1.03	0.99	0.79	0.1748
Sulfur, wt%	0.3	0.33	0.33	0.43	0.29	0.37	0.34	0.0515
Oxygen, wt%	20.23	19.55	20.17	19.44	19.68	18.74	19.64	0.5456
Heating Value, Btu/lb	9648	9565	9789	9728	10016	9619	9728	162
Calculated Parameters								
F_d, dscf/MMBtu	11937	12214	11814	11936	11342	12125	11895	307
Sulfur,[a] wt%	0.38	0.42	0.41	0.53	0.35	0.47	0.42	0.0645
Heating Value,[a] Btu/lb	12060	12047	12085	11936	12053	12099	12047	58
Hg,[b] µg/Nm^3	7.31	7.14	7.07	9.48	6.96	9.17	7.86	1.1485
Hg,[b] lb/TBtu	6.35	6.35	6.08	8.24	5.75	8.10	6.81	1.0760

[a] Dry basis.

[b] Flue gas basis.

Stack and SDA–FF Results – September 2006 Testing

Results for baseline and addition of SEAs are given in Tables 3 and 4 and Figure 5. As shown in Table 3, the average baseline total Hg concentration at the stack during September testing was 8.9 µg/Nm^3 based on CMM measurements, while OH measurements indicated a concentration of 10.9 µg/Nm^3. With the average coal mercury concentration of 13.08 µg/Nm^3 during this period, baseline Hg removal levels attained were 32% for CMM and 17% for the OH method. Injection of increasing amounts of Cl_2 into the flue gas resulted in an increase in the Hg removal levels. Addition of 600 ppm and 800 ppm of Cl_2 led to, respectively, 56% and 60% Hg removal from baseline or 70% from baseline and 73% from coal Hg levels. During addition of Cl_2 (600 ppm), the percent Hg removal determined using the OH method was about 58% relative to baseline OH values and 65% from the average coal Hg concentration. The next sorbent tested during this trip at the stack was PAC and/or SEA2. PAC alone injected at 1 lb/Macf afforded 40% and 59% removal from baseline and coal, respectively, while a combination of PAC and SEA2 yielded increasingly higher removal percentages as the amount of PAC and/or SEA2 was increased (see Table 3). As seen in this table, the maximum achieved Hg removal was about 86% from coal (or 79% from baseline) during addition of PAC at 3 lb/Macf and SEA2 at 18 lb/hr. These results are also depicted graphically in Figure 5; in Figure 6, example plots of CMM data obtained on September 21 and 22, 2006, are presented.

Table 13. Coal Properties During the November 29 to December 2, 2007, Testing

Property	11/29/07 Average	11/30/07 Average	12/02/07 Average	Overall Average	Standard Deviation
Mercury,[a] ppm	0.0777	0.0851	0.0772	0.08	0.0044
Chlorine,[a] ppm	13	11	12	12	1
Proximate Analysis					
Moisture, wt%	18.50	19.30	22.30	20.03	2.0033
Volatile Matter, wt%	37.11	36.42	34.96	36.16	1.0977
Fixed Carbon, wt%	39.56	39.28	37.85	38.90	0.9172
Ash, wt%	4.83	5.00	4.88	4.90	0.0874
Ultimate Analysis					
Hydrogen, wt%	5.86	5.87	6.03	5.92	0.0954
Carbon, wt%	56.27	55.52	53.39	55.06	1.4941
Nitrogen, wt%	1.01	1.02	0.99	1.01	0.0153
Sulfur, wt%	0.29	0.27	0.34	0.30	0.0361
Oxygen, wt%	31.73	32.32	34.36	32.80	1.3800
Heating Value, Btu/lb	9540	9428	9004	9324	283
Calculated Parameters					
F_d, dscf/MMBtu	9781	9750	9815	9782	33
Sulfur,[a] wt%	0.36	0.33	0.44	0.38	0.0569
Heating Value,[a] Btu/lb	11706	11683	11588	11659	63
Hg,[b] µg/Nm^3	9.32	10.26	9.32	9.63	0.5427
Hg,[b] lb/TBtu	6.64	7.28	6.66	6.86	0.3639

[a] Dry basis.
[b] Flue gas basis.

The results obtained at the SDA–FF during the September test period are presented in Table 4. Unlike the stack, only various amounts of Cl_2 were tested at the SDA in addition to baseline measurements. It is worth noting that this test location was particularly challenging and the CMM data were too noisy; consequently, the results obtained at the SDA are, from our perspective, not very reliable. Baseline Hg removal efficiencies obtained were 27% for CMM and 17% for the OH method. Addition of Cl_2 in the amounts of 600, 800, and 1000 ppm yielded very erratic results, which led to unrealistic negative Hg removal percentages from baseline and in some cases from coal. OH measurements were made during addition of Cl_2 and the same kind of perplexing numbers were obtained: 28% efficiency upon addition of Cl_2 (600 ppm), 24% for adding Cl_2 (800 ppm), and 17% for adding Cl_2 (1000 ppm) relative to average coal Hg levels. The performance determined by OH from baseline during addition of these amounts of chlorine was much worse: 14%, 8%, and 0.6% for adding 600, 800, and 1000 ppm equivalents of chlorine, respectively. This trend is contrary to our expectation and seems to underscore the challenging nature of this test location. An example plot of CMM data that shows the erratic behavior of data points during sorbent injection is shown in Figure 7.

Table 14. Summary of the Properties of Coal Samples Collected During Testing at HAW5

Property	Sept. 18–20, 2006 Avg.	Dec. 02–06, 2006 Avg.	July 12–17, 2007 Avg.	Nov. 29 – Dec. 02, 2007 Avg.	Overall Avg.	Standard Dev.
Mercury,[a] ppm	0.108	0.0929	0.0821	0.08	0.0908	0.0130
Chlorine,[a] ppm	14.2	16.3	13	12	14	2
Proximate Analysis						
Moisture, wt%	20.20	20.74	19.25	20.03	20.06	0.6161
Volatile Matter, wt%	34.41	33.67	33.69	36.16	34.48	1.1727
Fixed Carbon, wt%	40.14	40.29	41.44	38.90	40.19	1.0384
Ash, wt%	5.26	5.31	5.63	4.90	5.27	0.2962
Ultimate Analysis						
Hydrogen, wt%	6.11	6.10	5.49	5.92	5.90	0.2893
Carbon, wt%	54.28	54.00	68.12	55.06	57.86	6.8543
Nitrogen, wt%	0.99	0.97	0.79	1.01	0.94	0.1011
Sulfur, wt%	0.44	0.36	0.34	0.30	0.36	0.0603
Oxygen, wt%	32.92	33.29	19.64	32.80	29.66	6.6885
Heating Value, Btu/lb	9973	9336	9728	9324	9590	317
Calculated Parameters						
F_d, dscf/MMBtu	9139	9643	11895	9782	10115	1219
Sulfur,[a] wt%	0.56	0.45	0.42	0.38	0.45	0.0759
Heating Value,[a] Btu/lb	12,501	11780	12047	11659	11997	373
Hg,[b] µg/Nm^3	13.08	11.22	7.86	9.63	10.45	2.3310
Hg,[b] lb/TBtu	8.72	7.88	6.81	6.86	7.57	0.9113

[a] Dry basis.
[b] Flue gas basis.

Table 15. Summary Mercury Content in Ash and Slurry Samples from HAW5

Test Date	Average Ash Hg, ppm	Average Slurry Hg, ppm Solid	Average Slurry Hg, ppm Liquid
9/17–26, 2006	0.256	0.218	0.00002
12/1–6, 2006	0.706	–	–
7/12–17, 2007	0.846	0.508	0.0056
11/29 – 12/2, 2007	0.271	0.257	–

Stack and SDA–FF Results – December 2006 Testing

During the December 2006 test trip, many more parametric tests involving PAC, PAC/Cl_2 and PAC/SEA2 were performed, since addition of PAC in the September test round proved to yield better Hg removal levels. The results obtained at the stack are shown in Table 5 and total Hg removal efficiencies are also shown in Figure 8. The average baseline total mercury concentration during this period was about 8.8 µg/Nm^3 and the average coal Hg concentration was 11.22 µg/Nm^3, which gives an average baseline CMM Hg removal of about 22%. As shown in this table, the average OH Hg concentration during sorbent testing was 1.2 µg/Nm^3. This gives

Table 16. Coal Properties During Parametric Testing at MC4, June 2007

Property	6/25/07 Average	6/26/07 Average	6/27/07 Average	Overall Average	Standard Deviation
Mercury,[a] ppm	0.0833	0.0864	0.0839	0.0845	0.0016
Chlorine,[a] ppm	1210	1500	1400	1370	147
Proximate Analysis					
Moisture, wt%	4.3	3.1	3.5	3.6	0.6110
Volatile Matter, wt%	33.83	33.99	34.01	33.94	0.0987
Fixed Carbon, wt%	49.76	48.95	48.97	49.23	0.4620
Ash, wt%	12.1	13.95	13.52	13.19	0.9681
Ultimate Analysis					
Hydrogen, wt%	4.76	4.82	4.69	4.76	0.0651
Carbon, wt%	74.7	73.06	64.31	70.69	5.5858
Nitrogen, wt%	1.44	1.35	1.28	1.36	0.0802
Sulfur, wt%	2.94	3.02	2.97	2.98	0.0404
Oxygen, wt%	4.06	3.8	13.23	7.03	5.3709
Heating Value, Btu/lb	11817	11773	11807	11799	23
Calculated Parameters					
F_d, dscf/MMBtu	11142	11001	9425	10523	953
Sulfur,[a] wt%	3.07	3.12	3.08	3.09	0.0242
Heating Value,[a] Btu/lb	12348	12150	12235	12244	99
Hg,[b] μg/Nm^3	8.31	8.87	9.99	9.06	0.8530
Hg,[b] lb/TBtu	6.75	7.11	6.86	6.90	0.1872

[a] Dry basis.

[b] Flue gas basis.

Table 17. Mill Creek Baseline Results Obtained in This Study. All Measurements Were Corrected to Dry Basis at 3% O_2

Sample Number	ESP Inlet, μg/Nm^3				Wet FGD Outlet, μg/Nm^3				Hg removal, %	
	$Hg_{(p)}$	Hg^0	Hg^{2+}	$Hg_{(T)}$	$Hg_{(p)}$	Hg^0	Hg^{2+}	$Hg_{(T)}$	From Coal	ESP–FGD
1	0.08	1.50	19.32	20.90	0.04	1.80	0.68	2.52	72.2	88
2	0.04	0.21	13.27	13.52	0.05	1.13	0.60	1.78	80.4	86.8
3	0.04	0.49	12.71	13.24	0.00	1.28	0.55	1.83	79.8	86.2
4	0.03	0.24	12.11	12.38	0.01	1.38	0.42	1.81	80.0	85.4
Average	0.05	0.61	14.35	15.01	0.03	1.40	0.56	1.99	78.0	86.7

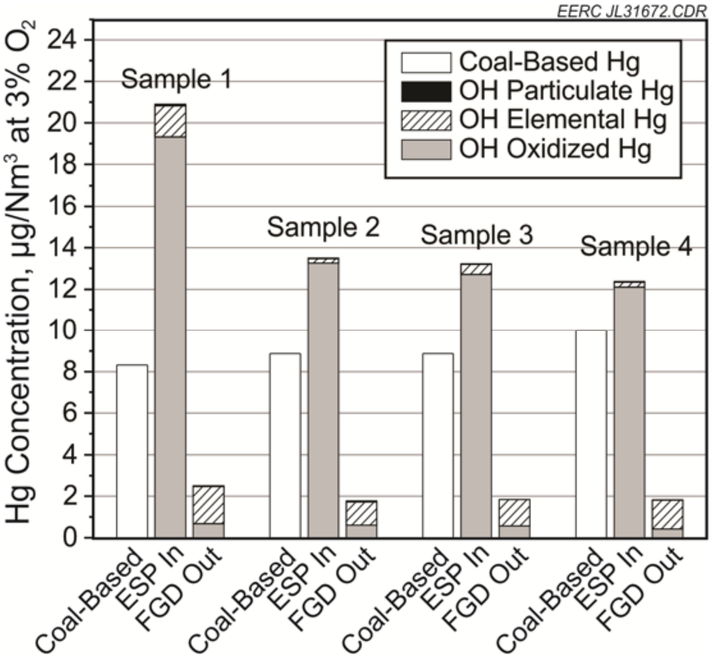


Figure 11. Comparison of coal-based and OH mercury concentrations during baseline tests.

Table 18. Speciated Chloride and SO_3 Levels

Sample	HCl	Cl_2	SO_3
1	18.7	1.5	23.0
2	100.5	2.4	18.2
3	90.6	2.4	19.7
4	78.9	1.5	–
Average	72.2	2.0	20.3

Table 19. Mercury Concentration in FGD Thickener Streams and ESP Ash Obtained During Baseline Testing

	Reaction Tank Hg Content		Underflow Hg Content		Overflow Hg Content		ESP Ash Analysis	
Sample Date	Solid Phase	Liquid Phase	Solid Phase	Liquid Phase	Solid Phase	Liquid Phase	Hg Content	LOI, %
6/25/07	0.317	0.0584	0.436	0.0055	2.43	0.0043	0.0511	0.84
6/26/07	N/A	N/A	N/A	N/A	N/A	N/A	0.0547	0.93
6/27/07	0.568	0.0253	0.308	0.0055	0.445	0.0095	0.038	0.85

Table 20. Dust-Loading Measurements at the ESP Inlet to FGD Outlet Determined by the OH Method at Baseline. Data Are Corrected to Dry Basis at 3% O_2

Sample	Dust Loading at ESP Inlet,[a] gr/dscf	Dust Loading at FGD Outlet,[a] gr/dscf	Particulate Removal Efficiency, %
6/25/2007	3.8543	0.0428	98.89
6/26/2007	2.6887	0.0242	99.10
6/26/2007	3.3292	0.0006	99.98
6/27/2007	2.9187	0.0020	99.93
Average	3.1957	0.0170	99.47

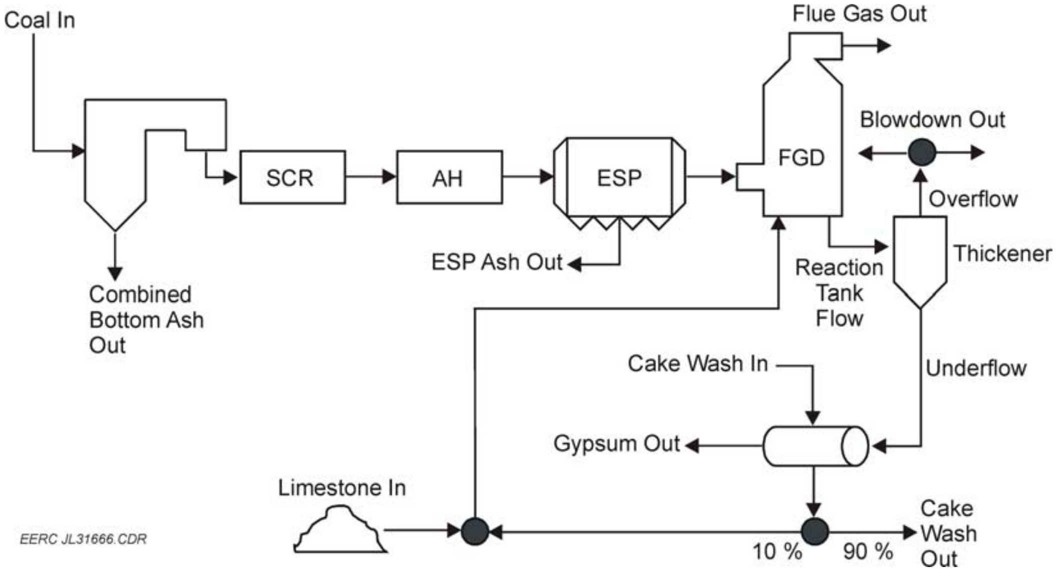


Figure 12. Simplified flow schematic of MC4.

Table 21. Primary Material Streams for the Mercury Mass Balance at MC4 During Baseline Sampling. Material Stream Quantities are Computed on a Dry Basis at 3% O_2

Material Stream	Magnitude Used for Mass Balance Calculations	Calculated Mass Flow of Hg, lb/hr
Coal Feed In	417,000 lb/hr	0.0353
Limestone In	41,600 lb/hr	0.000166
Stack Out	634×10^5 dscf/hr	0.00787
ESP Ash Out	45,500 lb/hr	0.00218
Underflow Out	268,400 lb/hr	0.02542
Overflow or Blowdown Out	26,700 lb/hr[a]	0.00200

[a] There were insufficient data to estimate the magnitude of the chloride blowdown stream during baseline testing; consequently, this value was determined based on data collected during long-term testing as described in the appendix.

Table 22. Brief Descriptions of the Technologies Used for Parametric Tests Conducted at MC4

Test Date	Technology	Test Condition	Location
7/10/2007	ACI	0.5 lb/Macf	ESP inlet
7/10/2007	ACI	1.0 lb/Macf	ESP inlet
711/2007	ACI	1.5 lb/Macf	FGD slurry
7/11/2007	ACI and B&W additive	1.0 lb/Macf and 60 g/hr	ESP inlet/FGD slurry
7/12/2007	B&W additive	30 g/hr	FGD slurry
7/12/2007	B&W additive	45 g/hr	FGD slurry
7/16/2007	SEA2	2.5 lb/hr	SCR inlet
7/16/2007	SEA2	5 lb/hr – Incomplete	SCR inlet
7/18/2007	ACI and SEA2	1.0 lb/Macf and 5 lb/hr	ESP inlet
7/19/2007	ACI and SEA2	1.0 lb/Macf and 2.5 lb/hr	ESP inlet
7/20/2007	ACI and SEA2	1.0 lb/Macf and 5 lb/hr	ESP inlet
7/24/2007	ACI	1.0 lb/Macf	ESP inlet
7/24/2007	ACI and B&W additive	1.0 lb/Macf and 30 g/hr	ESP inlet/FGD slurry
7/24/2007	ACI and B&W additive	1.0 lb/Macf and 80 g/hr	ESP inlet/FGD slurry
7/24/2007	B&W additive	80 g/hr	FGD slurry

Table 23. Results of Parametric Tests at MC4 Measured Across the ESP Inlet and Wet FGD Outlet Using a CMM. Data Have Been Corrected to Dry Basis at 3% O_2

Test Condition	Coal Hg, µg/Nm^3	Avg. ESP Inlet Hg, µg/Nm^3	Avg. FGD Outlet Hg, µg/Nm^3	Coal–FGD Hg Removal, %	ESP–FGD Hg Removal, %
ACI 0.5 lb/Macf	10.52	12.81	4.16	60.5	67.6
ACI 1.0 lb/Macf	10.52	12.46	3.45	67.2	72.3
ACI 1.5 lb/Macf	9.90	13.80	2.39	75.9	82.7
ACI 1.0 lb/Macf	9.03	7.67	2.16	76.1	71.8
B&W 30 g/hr	7.81	10.30	1.29	83.5	87.5
B&W 45 g/hr	7.81	12.83	1.12	85.7	91.3
B&W 80 g/hr	9.03	Offline	0.83	90.8	–
ACI 1.0 lb/Macf and B&W 30 g/hr	9.03	12.09	2.88	68.1	87.9
ACI 1.0 lb/Macf and B&W 60 g/hr	9.90	Offline	1.46	85.3	–
ACI 1.0 lb/Macf and B&W 80 g/hr	9.03	Offline	0.97	89.3	–
SEA2 2.5 lb/hr	8.99	8.27	2.39	73.4	71.1
SEA2 5 lb/hr – Incomplete	8.99	8.04	2.33	74.1	71.0
ACI 1.0 lb/Macf and SEA2 2.5 lb/hr	9.71	6.16	2.61	73.1	57.6
ACI 1.0 lb/Macf and SEA2 5 lb/hr	9.61	7.79	2.70	71.9	65.4
ACI 1.0 lb/Macf and SEA2 5 lb/hr	10.14	5.39	2.21	78.2	59.0

Table 24. Mill Creek Baseline Results Obtained in a Previous Study with SCR In Service and SCR Bypassed

Sample	SCR Inlet, $\mu g/Nm^3$	SCR Outlet, $\mu g/Nm^3$	Wet FGD Inlet, $\mu g/Nm^3$	Stack, $\mu g/Nm^3$	Removal, %
SCR In Service					
$Hg_{(p)}$	0.02	0.03	0.00	0.00	
Hg^0	8.32	2.83	0.33	3.97	
Hg^{2+}	0.94	5.05	7.60	0.54	
$Hg_{(T)}$	9.27	7.90	7.93	4.50	43.3
SCR Bypassed					
$Hg_{(p)}$			0.07	0.05	
Hg^0			2.44	2.63	
Hg^{2+}			6.79	0.55	
$Hg_{(T)}$			9.30	3.23	65.3

Table 25. Vapor-Phase Mercury Concentration ($\mu g/m^3$) Measured Using Sorbent Traps (corrected to dry basis at 3% O_2) Compared with CMM Measurements. The Difference Represents How Much Larger the Sorbent Trap Values Are Over the CMM Values

Parametric condition	Average Sorbent Trap Hg Concentration, $\mu g/Nm^3$	Average CMM Hg Concentration, $\mu g/Nm^3$	Difference
ACI 1.0 lb/Macf into ESP Inlet and B&W Additive at 80 g/hr	1.01	0.63	0.38
B&W Additive at 80 g/hr	0.78	0.54	0.24
SEA2 into SCR Inlet at 2.5 lb/hr	2.55	1.56	0.99
ACI 1.0 lb/Macf and SEA2 5.0 lb/hr into ESP Inlet[a]	3.03	1.76	1.27
ACI 1.0 lb/Macf and SEA2 2.5 lb/hr into ESP Inlet[b]	2.95	1.70	1.25

[a] SEA2 stopped after approximately 30 minutes of sampling.

[b] SEA2 stopped after approximately 20 minutes of sampling.

an average Hg removal of essentially 90% based on average coal Hg levels. As expected, addition of PAC/Cl_2 in increasing amounts yields correspondingly better results, with a maximum achieved removal of 85% upon addition of PAC at 3.6 lb/Macf and 1200 ppm of Cl_2. This happens to be a similar percent removal seen during the September testing period when PAC 3 lb/Macf and SEA2 18 lb/hr were injected into the flue gas stream. Changes in the amount of added PAC to 322 lb/hr and maintaining Cl_2 levels at 1200 ppm led to Hg removal level of 89.3%, which is just shy of the 90% removal target. Interestingly, slightly increasing the amount of PAC to 420 lb/hr did not seem to improve removal efficiencies, thus indicating that an optimum PAC addition amount might have been reached. Not shown in Table 5 or Figure 8 are some specific results based on OH measurements: addition of PAC (3.3 lb/Macf) and Cl_2 (1000 ppm), PAC (3.6 lb/Macf) and Cl_2 (1200 ppm), PAC (300 lb/hr) and SEA2, and PAC (322 lb/hr) and Cl_2 (1200 ppm) afforded 80%, 96%, 86%, and 95% Hg removal efficiencies, respectively, from the average coal concentration of 11.22 $\mu g/Nm^3$.

Table 26. Average Coal Properties During Long-Term Testing (8/28/07 to 10/1/07) at MC4

Property	Average Values
Mercury,[a] ppm	0.1000
Chlorine,[a] ppm	1175
Proximate	
Moisture, wt%	10.09
Volatile Matter, wt%	35.84
Fixed Carbon, wt%	44.49
Ash, wt%	9.58
Ultimate Analysis	
Hydrogen, wt%	5.52
Carbon, wt%	66.62
Nitrogen, wt%	1.63
Sulfur, wt%	3.07
Oxygen, wt%	13.58
Heating Value, Btu/lb	11306
Calc. Parameters	
F_d, dscf/MMBtu	10424
Sulfur,[a] wt%	3.41
Heating Value,[a] Btu/lb	12575
Hg,[b] µg/Nm^3	10.47
Hg,[b] lb/TBtu	7.95

[a] Dry basis.
[b] Flue gas basis.

Similar to what was observed during the September testing at SDA, the results obtained during the December test period were also very erratic and occasionally show negative percent Hg removal levels (see Table 6). The average baseline Hg concentration at the SDA was 10.2 µg/Nm^3, compared to 8.8 µg/Nm^3 obtained at the stack. Although there was no baseline OH measurement at the stack, the one obtained at the SDA was 11.8 µg/Nm^3; yet this is smaller than some of the values obtained by CMM during sorbent injection. Because of these relatively high average total Hg levels even during sorbent injection, there are some negative percent Hg removals from average baseline or from the average coal value. Similar poor performances were observed with the OH data during sorbent testing. When PAC (3.6 lb/Macf) and Cl_2 (1200 ppm) were added, the percent removal was 58% from baseline and 56% from coal, but during addition of PAC (3.3 lb/Macf) and Cl_2 (1000 ppm), the calculated percent removal by OH was 4% from baseline and −0.6% from coal. When PAC alone was added at the rate of 3 lb/Macf, the performance based on OH measurements was worse: −9% from baseline and −0.1% from coal Hg levels. As mentioned earlier, these data obtained at the SDA–FF were so erratic that they were not used in making any determinations of the optimum conditions or to determine the best technology that can achieve >90% Hg control efficiency.

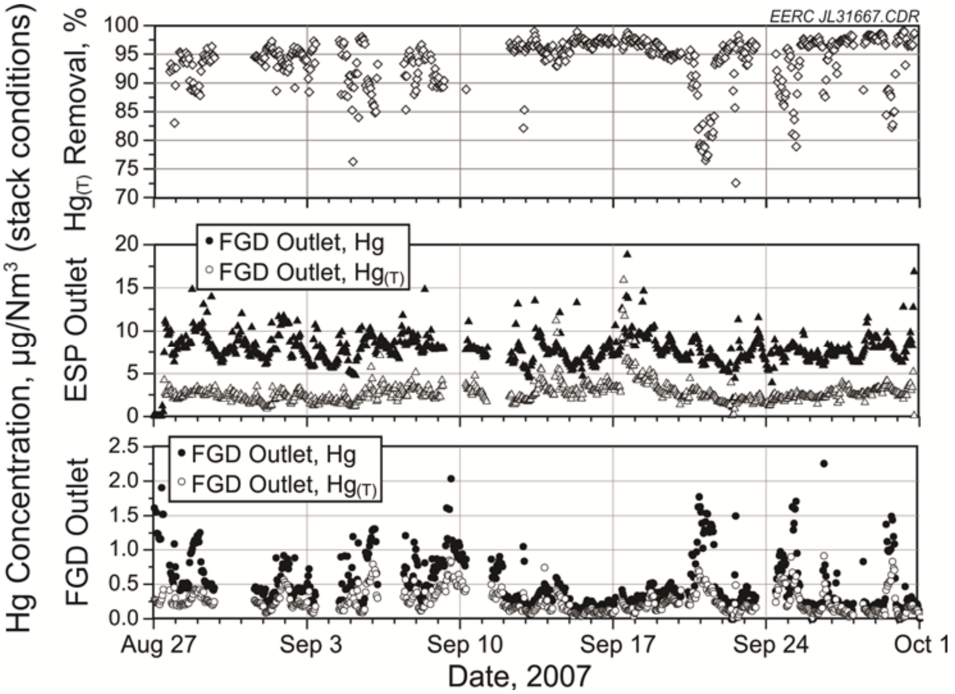


Figure 13. Hourly average CMM-based mercury removal (top) and CMM data at the ESP (middle) and FGD (bottom) outlets. Data points corresponding to periods when additive addition was interrupted have been removed.

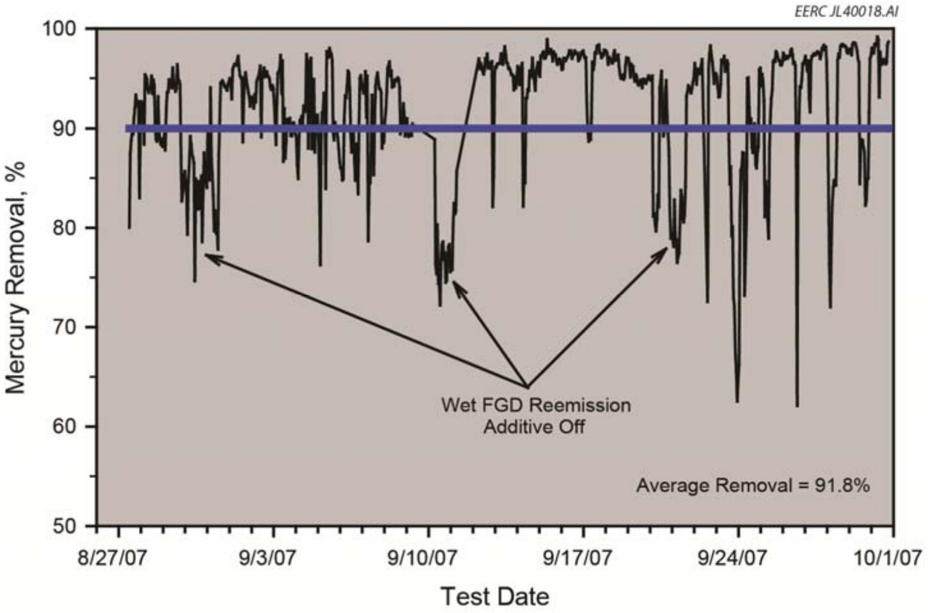


Figure 14. Plot of mercury removal efficiencies obtained at MC4 during long-term testing over a period of 1 month.

Table 27. Summary of M30B (sorbent trap) Results During Long-Term Test at MC4. Mercury Concentrations Are Corrected to Dry Basis at 3% O_2

	ESP Outlet Hg, µg/Nm^3		FGD Outlet Hg, µg/Nm^3		ESP-Out to FGD-Out Hg Removal, %
Test Date	M30B	CMM	M30B	CMM	
8/28/07	12.01	12.09	0.64	0.73	94.7
8/28/07	11.91	11.19	1.53	1.47	87.1
8/29/07	12.50	12.65	1.08	0.74	91.3
8/29/07	10.84	10.95	0.61	0.68	94.4
9/24/07	11.31	9.85	1.37	1.12	87.9
9/26/07	10.12	9.97	0.34	0.24	96.6
9/27/07	11.14	10.05	0.45	0.29	95.9
9/27/07	12.04	10.29	0.37	0.27	96.9

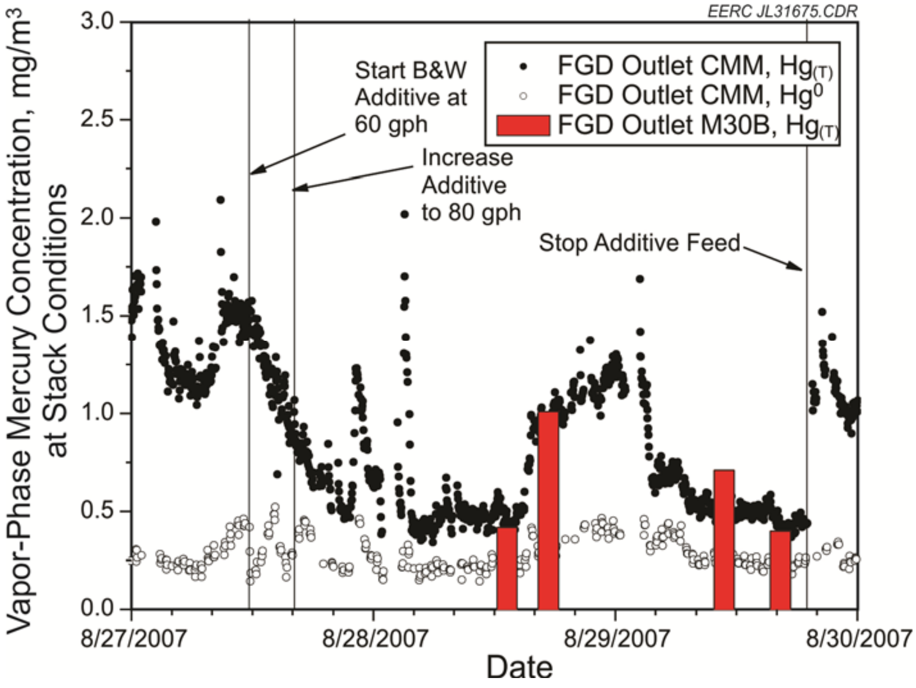


Figure 15. M30B and CMM results obtained at the FGD outlet during the first week of long-term testing.

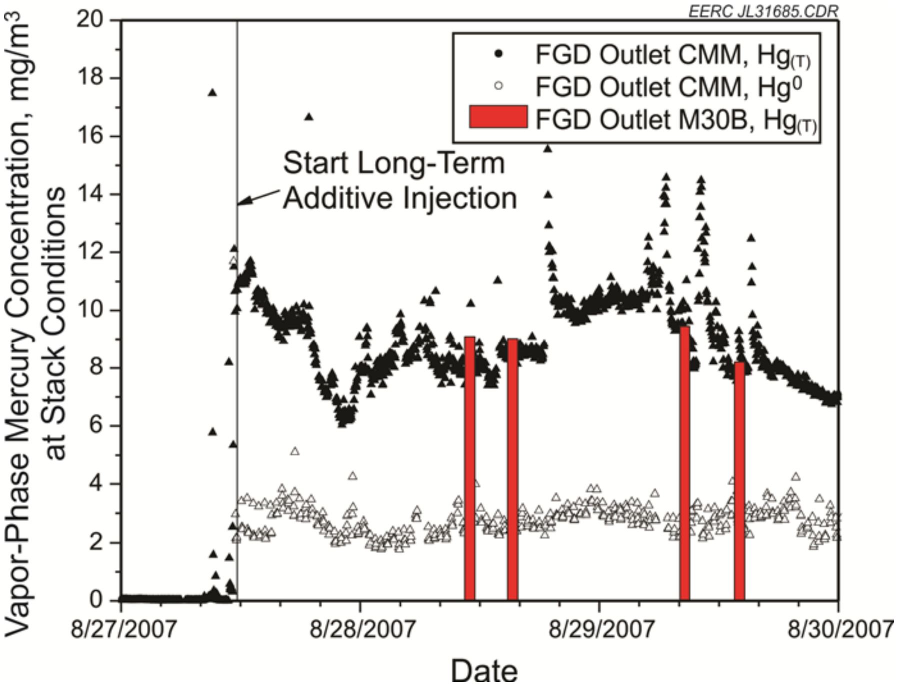


Figure 16. M30B and CMM results obtained at the ESP FGD outlet during the first week of long-term testing.

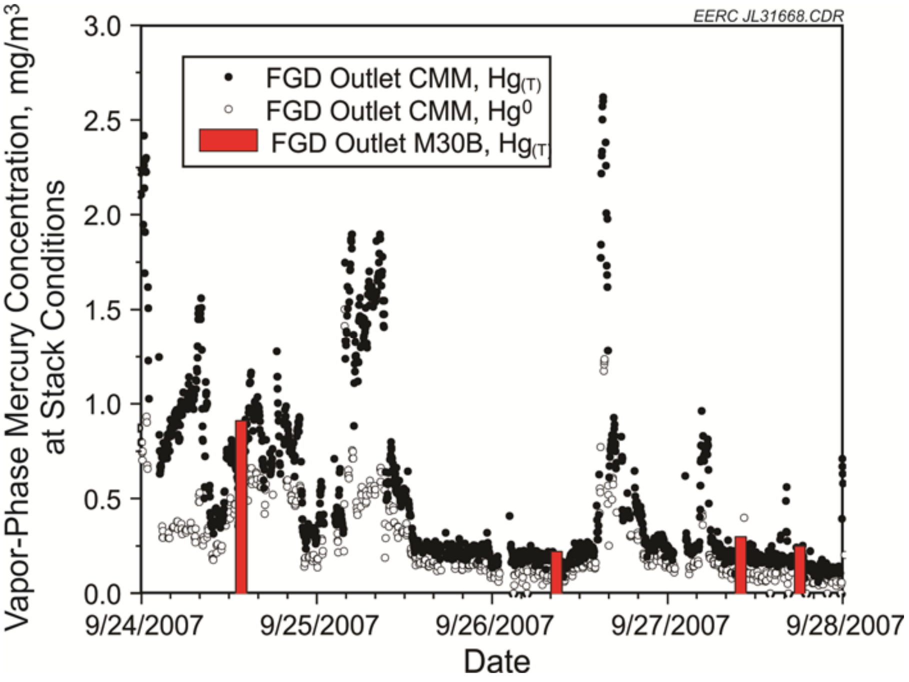


Figure 17. M30B and CMM results obtained at the FGD outlet during the last week of long-term testing.

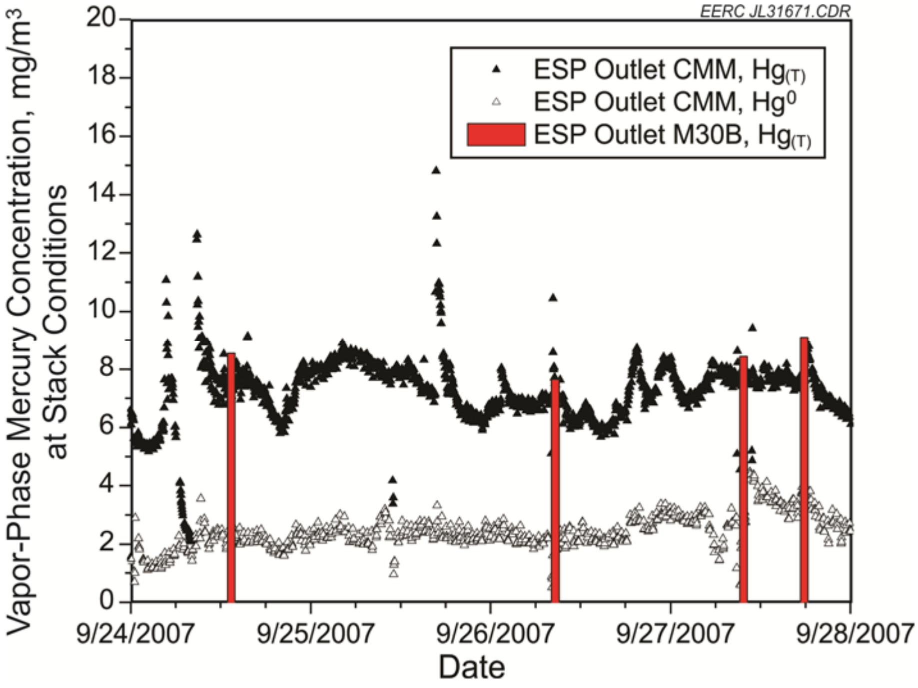


Figure 18. M30B and CMM results obtained at the ESP outlet during the last week of long-term testing.

Table 28. Method 29 Measurements of Hg Concentrations During Long-Term Test at MC4. Data Corrected to Dry Basis at 3% O_2

Sample Date	ESP Inlet Total Hg, µg/Nm^3	ESP Outlet Total Hg, µg/Nm^3	FGD Outlet Total H, µg/Nm^3
9/25/2007	9.43	11.4	0.669
9/27/2007	12.5	12.7	0.552
9/28/2007	11.5	13.1	0.729
Average	11.1	12.4	0.65

Table 29. Mercury Concentrations in the FGD Thickener Flow Streams During the Long-Term Test at MC4

Flow Stream	Solids, %	Avg. Hg Content of Solid Fraction,[a] ppm	Avg. Hg Content of Liquid Fraction,[a] ppm	Total Mass, %
Reaction Tank In	10.7	0.708	0.0302	100
Underflow Out	29.1	0.319	0.00470	25.1
Overflow Out	4.78	1.15	0.0438	74.9

[a] Mass basis.

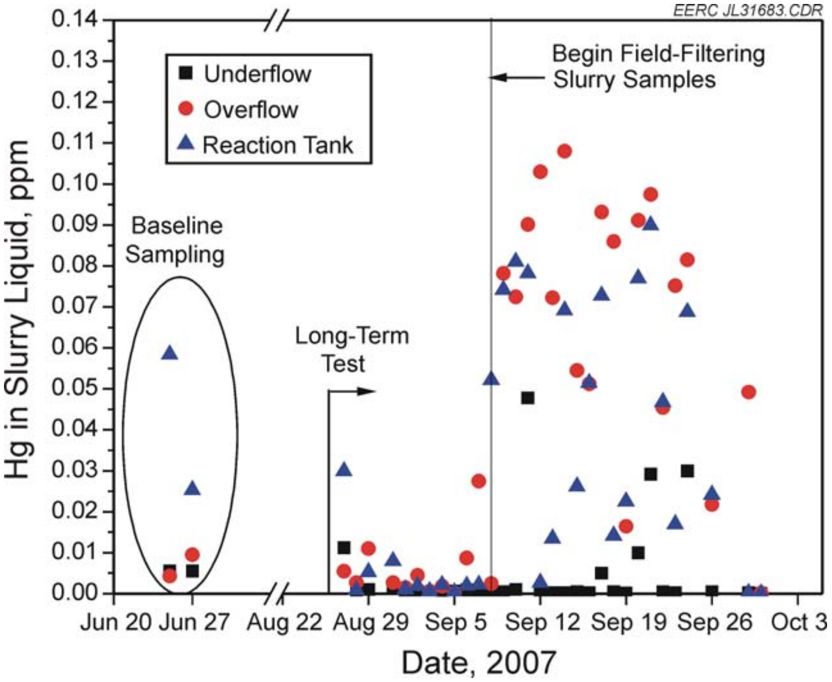


Figure 19. Mercury concentration of the liquid portions of the FGD slurry samples during baseline and long-term testing.

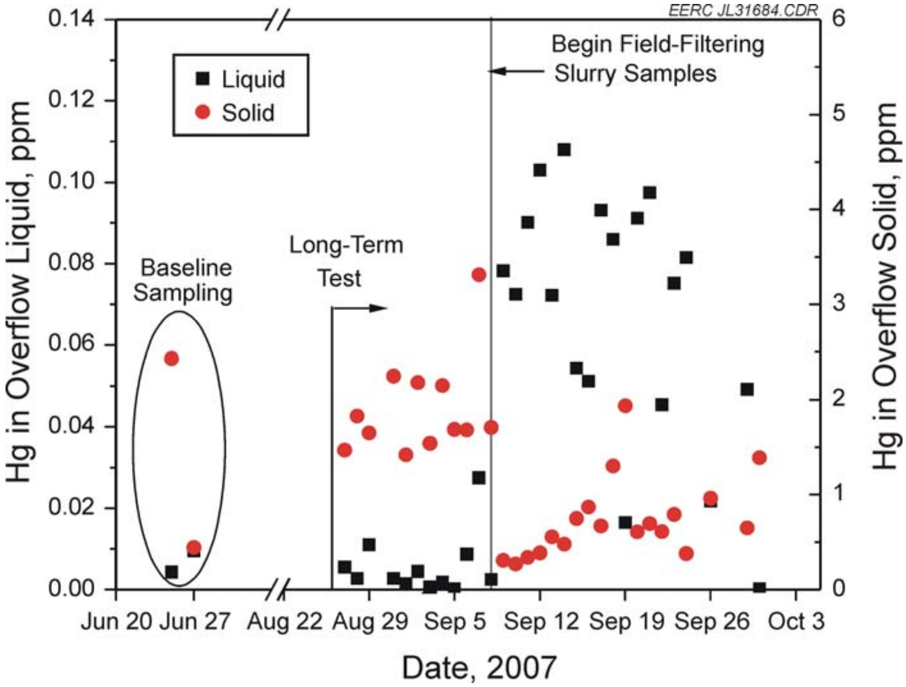


Figure 20. Mercury concentration of the liquid and solid portions of the overflow slurry samples during baseline and long-term testing.

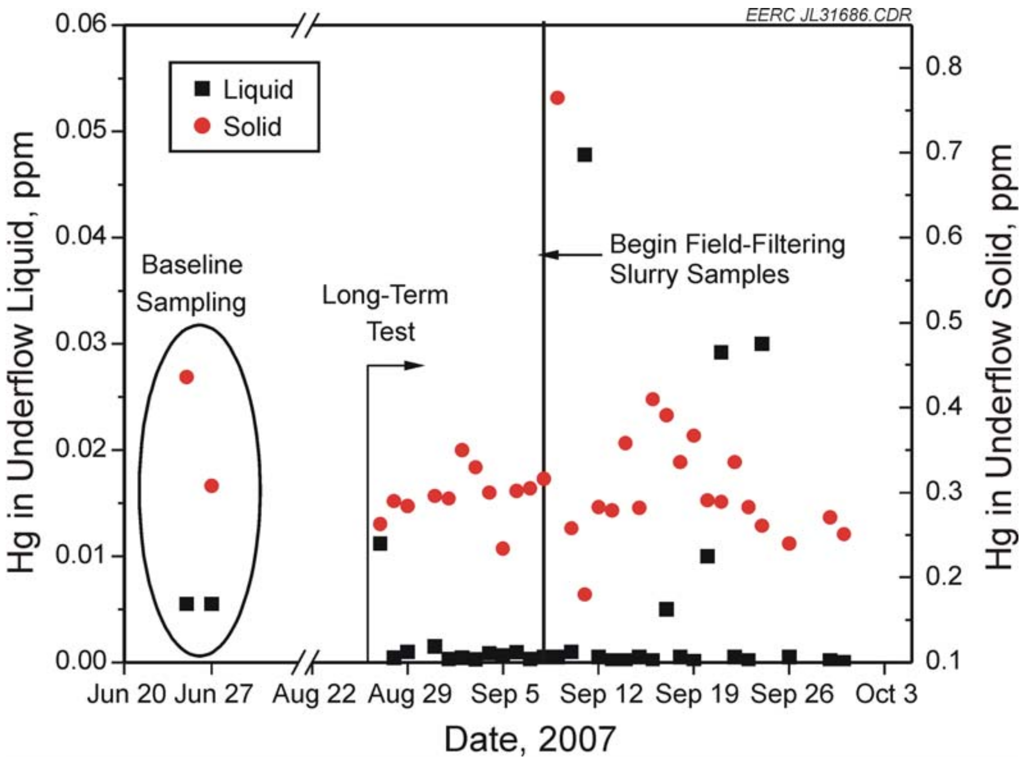


Figure 21. Mercury concentration of the liquid and solid portions of the underflow slurry samples during baseline and long-term testing.

Table 30. Primary Material Streams for MC4 During the Long-Term Test

Material Stream	Magnitude Used for Mass Balance Calculations	Calculated Mass Flow of Hg, lb/hr
Coal Feed In (dry)	326,000 lb/hr	0.0373
Limestone In	37,600 lb/hr	0
Stack Out	524×10^5 dscf/hr at 3% O_2	0.00213
ESP Ash Out	29,400 lb/hr	0.00126
Underflow Out	196,100 lb/hr	0.021939
Overflow or Blowdown Out	26,700 lb/hr	0.00296

Table 31. Gypsum Mercury Concentrations

Sample Date	Test Condition	As-Received Hg,[a] ppm	Hg,[a] ppm
7/13/07	Baseline	0.217	0.282
8/28/07	Long-Term Week 1	0.241	0.320
8/29/07	Long-Term Week 1	0.248	0.317
9/17/07	Long-Term Week 4	0.135	0.175

[a] Dry mass basis with average as-received moisture content of 23%.

Stack Results – July 2007 Testing

In subsequent test rounds, i.e., July 11–17 and November 29 to December 2, 2007, measurements were only made at the stack because the SDA location was determined (based on the results of the previous tests) to be very challenging and the data obtained at the SDA were too noisy and not very meaningful or reliable. The results obtained during the July 2007 testing are presented in Table 7 and Figure 9. During this test period, the average coal Hg concentration was 7.86 $\mu g/Nm^3$ and baseline CMM and OH average total Hg concentrations were 6.5 $\mu g/Nm^3$ and 7.1 $\mu g/Nm^3$, respectively, for an average baseline removal of 17.5% for CMM and 9.7% for OH. Two main technologies were tested during this period, including addition of various amounts of Cl_2 and adding a mixture of Cl_2 and PAC. As seen in Table 7, upon varying the amount of added Cl_2 from 600 ppm to 1200 ppm, there appears to be a peak performance of 80% at 800 ppm. Although adding 1200 ppm of Cl_2 gives essentially the same results, addition of 1000 ppm of Cl_2 is about 3 percentage points lower in performance than adding 800 ppm. As a result, 800 ppm of Cl_2 seems to be a cost-effective amount of additive that gives the best performance for using a Cl_2-only additive. However, combining Cl_2 and PAC was found to give much better results: adding only 500 ppm of Cl_2 and PAC (2 lb/Macf) afforded 94% total Hg removal from coal concentrations (see Table 7 and Figure 9). This, therefore, is a possible optimum condition for achieving >90% mercury removal from coal mercury levels. EPA Method 29 (M29) measurements were also taken during this test trip and the M29 baseline Hg concentration was 6.6 $\mu g/Nm^3$, which was in agreement with the CMM value of 6.5 $\mu g/Nm^3$. The M29 average total Hg determined during injection of 800 ppm of Cl_2 and during injection of 250 ppm of Cl_2 and PAC (2 lb/MMBtu) was 0.75 $\mu g/Nm^3$, for an average coal removal of 90.4% and baseline removal of 88.5%. OH measurements taken during injection of Cl_2 (500 ppm) and PAC (2 lb/Macf) indicated a 93.6% Hg removal from coal and 93% from baseline, being almost identical to the CMM results shown in Table 7 or Figure 9.

Stack Results – November/December 2007 Testing

During the November 29 – December 2, 2007, test period, the primary focus was on testing the performance of the DARCO Hg-LH and DARCO Hg additives. These results are presented in Table 8 and graphically in Figure 10. The average coal Hg concentration was found to be 9.63 $\mu g/Nm^3$, and the average baseline CMM and OH total Hg levels were 6.4 and 7.4 $\mu g/Nm^3$, respectively. Based on the coal Hg level, the baseline removal efficiency was 33% for CMM and 23% for OH. Upon addition of various amounts of DARCO Hg-LH (from 1 lb/Macf to 3 lb/Macf), the performance rises from 73%–93%, but the DARCO Hg additive passes through a maximum performance of 81%, which corresponds to addition of DARCO Hg (2 lb/Macf). It turns out that injecting the DARCO Hg through the high-temperature discharge (HTD) skid afforded essentially the same results (i.e., 79.4%, see Table 8) as if it were added regularly. Another interesting thing to note about these results is that the levels of elemental Hg were observed to be higher than those of total Hg, which may be an indication that the high-temperature discharge DARCO Hg-LH and DARCO Hg technology may not be effectively converting elemental Hg to its oxidized form. This is contrary to what was observed during testing of the other technologies mentioned earlier.

Comparison of Tested Technologies

The performance of all additives tested and their proportions are compared in Table 9. As shown in this table, two technologies were identified that are able to achieve >90% total Hg removal from coal mercury levels and two that are less than 1% short of attaining 90% removal. Addition of PAC (2 lb/Macf) in combination with Cl_2 (500 ppm) showed the highest performance of 94% and the DARCO Hg-LH additive (3 lb/Macf) comes close at 93%. Injection of PAC (322 lb/hr)/Cl_2 (1200 ppm) and DARCO Hg-LH (2 lb/Macf) each show great potential for achieving 90% Hg removal as well. Based on baseline Hg levels, only one technology (i.e., PAC [2 lb/Macf] and Cl_2 [500 ppm]) was found to meet the target of >90% removal. However, four other technologies shown in Table 9 show efficiencies of >85% from baseline, with the DARCO Hg-LH at an add rate of 3 lb/Macf attaining practically 90% Hg removal.

The procedure for finding the best technologies that can achieve >90% Hg removal efficiencies was quite methodical. In September 2006, PAC/SEA2 showed promising trends of achieving the target, but fell short by about 5%. In December of 2006, PAC was used in combination with Cl_2 to show that the target could possibly be met; the highest removal level during this test period was 89.3%. In July of 2007, with further fine tuning of the injection conditions, it was finally demonstrated that 94% removal level was achievable. The last technology that was demonstrated to be able to meet the >90% Hg removal target was the DARCO Hg-LH additive, as indicated above.

These technologies are developed based on a deeper understanding of the chemistry of mercury's interactions and speciation in combustion flue gases acquired by the EERC over the years. It is well known that particulate-bound and oxidized forms of Hg are easily captured by various types of scrubbers, but the elemental form is the most difficult to control because of the high volatility of mercury even at relatively low temperatures. Hence, research at the EERC has focused on chemical agents (e.g., chlorine) that enhance oxidation of the elemental form of Hg when injected into flue gas streams. These chemical agents, generally described as sorbent enhancement additives (SEAs) are used with powder activated carbon (PAC) sorbents or alone to effect greater Hg removal efficiencies. Sometimes, the new PRB coals contain higher levels of Na that may interfere with both the SCR and the Cl_2 levels in flue gas and impact negatively the performance of both of these chemical agents and the available control devices. Sodium, for example, will act as a blinding agent in the SCR system and prevent the Hg from getting to the active sites on the catalyst as well as react with the chloride species, making it unavailable to enhance Hg oxidation. Such problems are often encountered with most PRB coals as seen in this study at the HAW5 station.

Analysis of Coal and Ash Samples

Coal, ash, and slurry samples were taken periodically during testing at HAW5 and were analyzed at the EERC. The coal samples were analyzed for proximate and ultimate properties and for chlorine and mercury levels, while the ash and limestone slurry samples were analyzed for Hg concentration. In general, coal Hg levels were consistent for all coal samples analyzed from the different trips and are typical for a PRB coal. Results from these analyses are given in Tables 10–13, and a succinct summary over the four test periods is given in Table 14, while Hg measurements from the analysis of ash and slurry samples are presented in Table 15. In all samples collected during the entire sampling/testing at HAW5, chlorine levels were found to be typically low, about 10–21 ppm, with an overall average of only 14 ppm. Such levels are typically seen for most PRB coals.

A summary of the properties of coal samples collected during the September 2006 testing period is given in Table 10. The levels of chlorine in the coal are low, ranging from 10 to about 21 ppm, with an average of 14 ppm. This is very similar to what is known previously about this type of coal. The average coal mercury content was found to be 0.108 ppm, which corresponds to an inlet Hg concentration (calculated from the coal data) of 13.08 $\mu g/Nm^3$. Coal properties based on proximate and ultimate analysis show that there is about 20% moisture on average, low ash content (about 5%), high carbon content (54%), low sulfur and nitrogen content (each <1% on average) and a heating value of 9973 Btu/lb. Mercury concentrations measured in the ash showed that there is no significant impact from using the Hg control technologies as compared to baseline values. Ash samples collected over this period (i.e., September 18–26, 2006) showed that the amount of Hg varied from 0.213 ppm to 0.359 ppm, with an average ash mercury content of about 0.256 ppm (see Table 15). Calculated properties corrected to dry basis at 3% oxygen and flue gas basis are also given for comparison, and these have been determined for all test rounds at HAW5.

The properties of coal samples collected during the December 2–6, 2006, test period are shown in Table 11. The average coal Hg content, 0.093 ppm, was slightly lower than previously seen during the September test period but is normal for a typical PRB coal. The average chlorine content was slightly higher (16 ppm) than that seen during September testing, i.e., ranging from 12 to about 21 ppm. However, such levels are still considered very low and typical of PRB coals. Based on the “as-received” coal properties, an inlet coal Hg concentration of 11.22 $\mu g/Nm^3$ was determined. The properties determined from proximate and ultimate analysis are essentially similar to those seen for the coal samples collected during the September testing trip. The coal heating value was 9336, slightly lower than was measured for the coal samples taken in September, although the ash, carbon, sulfur, and moisture contents were largely similar. Ash samples collected over this period (i.e., December 2–6, 2006) showed that the amount of Hg varied from 0.599 ppm to 0.859 ppm, with an average ash mercury content of about 0.781 ppm (see Table 15).

Tests conducted in July of 2007 showed that the average coal Hg content was 0.082 ppm (see Table 12), being slightly lower than the levels seen in December or September of 2006. The amount of chlorine ranged from 9–14 ppm, with an average of 13 ppm. An average inlet Hg concentration of 7.86 $\mu g/Nm^3$ was calculated based on the measured coal proximate and ultimate properties, which was the lowest coal Hg level seen throughout the entire testing at HAW5. The moisture level was also slightly lower (19%) compared to 20% obtained during the other trips. There was a noticeable increase in the carbon content, 68% compared to 54% in the other samples. However, sulfur and nitrogen contents continue to be low at less than 1% each and ash levels of roughly 5%. Ash samples collected over this period (i.e., July 2007, see Table 15) showed that the amount of Hg varied from 0.579–1.065 ppm, with an average ash mercury content of about 0.846 ppm.

The last round of tests was carried out from November 29 to December 2, 2007. During this period, coal samples analyzed showed an average Hg level of 0.08 ppm, which corresponds to an inlet mercury concentration of 9.63 $\mu g/Nm^3$. The average chlorine content was 12 ppm. Results of the proximate and ultimate analysis on the coal samples collected during this trip showed a similar 20% moisture level, 5% ash content and carbon content of about 55% on average. Even though the sulfur content, continues to be low at less than 1%, the nitrogen content was slightly higher (about 1% on average). Despite the slight increase in nitrogen levels, it still does not appear to be of any such significance to cause concerns. Analysis of ash samples collected during this trip showed an average Hg content of 0.271 ppm, and the slurry samples had an average of 0.257 ppm of mercury (see Table 15).

A summary of averages of the coal properties obtained over the four test rounds at HAW5 is given in Table 14. As seen in this table, the overall average coal Hg content was found to be 0.091 ppm, which corresponds to an average coal Hg inlet concentration of 10.45 $\mu g/Nm^3$ determined from the "as-received" coal proximate and ultimate properties. In general, these results show that these coals are low in sulfur and nitrogen content and have ash content of about 5%. The moisture level is more or less constant at about 20% and the heating value can be expected to be in the neighborhood of 10,000 Btu/lb. The results shown in Table 15 on the analysis of ash and slurry samples show that there is an insignificant amount of Hg in the liquid portion of the slurries, while the Hg levels found in the solid portions are similar to those of the corresponding ash samples.

Mill Creek Unit 4

The primary technologies tested at MC4 include SEA2-T2, PAC, and B&W scrubber additives and various combinations of these techniques. As in the case of HAW5, baseline measurements were made prior to parametric tests. However, more tests were conducted at MC4 than at HAW5, including coal analysis, SO_3, and chloride speciation levels, analysis of the FGD thickener streams and LOI. In addition, more detailed EPA Method 30B (sorbents trap) testing was done at MC4 to compare with CMM and OH results. This batch of tests was completed for each of the baseline, parametric, and long-term test periods. These results are presented and discussed below in the order of baseline, parametric, and long-term.

Baseline Results

Determination of baseline conditions has always been a routine starting point for any demonstration tests carried out by the EERC at any power plant. During the tests at MC4, a series of baseline tests were performed, including analysis of coal samples for chlorine and mercury content as well as to obtain detailed properties of the coal, such as its heating value and proximate and ultimate analysis. Samples of the ESP ash and scrubber streams were also analyzed for Hg and LOI value, and the flue gases were analyzed for mercury speciation, chloride, and SO_3. To conclude the batch of baseline tests, a mercury mass balance was carried out to account for mercury going through the system before the mercury control technologies were applied. The results of these tests are presented below.

Coal Characteristics

Three daily coal samples were collected during baseline testing, and the results of the analysis are presented in Table 16. The average coal mercury and chloride contents were 0.085 and 1370 ppm, respectively. The moisture level of the coal is relatively low; the ash, sulfur, and nitrogen contents as well as the heating value are higher than those seen for PRB coals. These results are consistent with what is known about typical high-sulfur eastern bituminous coal. A dry emission factor, F_d, was calculated from the baseline coal proximate and ultimate properties on an "as-received" basis and was used to estimate the flue gas concentration of mercury. These calculations indicate that 0.085 ppm of Hg in the coal is approximately equal to 9.06 $\mu g/Nm^3$ of Hg in the flue gases, which is roughly equal to 6.9 lb/TBtu.

Analysis of Flue Gases

The flue gases were analyzed during baseline testing by carrying out four OH measurements at the ESP inlet and the wet FGD outlet; the results are presented in Table 17. In this table, the mercury concentration at the wet FGD outlet is about 2.0–3.0 $\mu g/Nm^3$, which is similar to the results of a previous study at this plant. Based on the average coal mercury concentration of 9.09 $\mu g/Nm^3$, this corresponds to 70%–80% baseline Hg removal efficiency. However, the data collected across the ESP and wet FGD (see Table 17) show baseline removal efficiencies in the range 72%–87%. Also, more elemental mercury was measured at the FGD outlet than at the ESP inlet. The average elemental mercury concentration detected at the ESP inlet was 0.61 $\mu g/Nm^3$, while at the FGD outlet, it was 1.4 $\mu g/Nm^3$, which is more than double the amount at the ESP inlet. This appears to confirm earlier reports of elemental mercury reemission from the wet FGD at the Mill Creek station, although not at the same level. The results of Table 17 are presented graphically in Figure 11, along with coal-based mercury concentrations. As seen from this figure, there is a difference between the OH-measured values and those based on the coal mercury content, with the OH data consistently higher than the coal-based values. This difference is not particularly surprising because that test location was a difficult one, and fluctuations in the data can be expected. It is believed that this might have affected the baseline mercury removal values shown in Table 17, where the average coal-to-FGD outlet removal was 78% and the ESP inlet-to-FGD outlet removal was 86.7%. No further Hg sampling (except CMM measurements) was conducted at the ESP inlet until the long-term test, and these subsequent measurements agreed well with the coal-based numbers. Coal-based Hg inlet values were used to evaluate Hg removals during parametric tests.

Chloride and Sulfur Trioxide Levels

Additional tests were performed on the flue gases to determine the chloride and SO_3 levels at the ESP outlet, and the results are presented in Table 18. As seen in this table, the average concentration of SO_3 is 20.3 ppm at the ESP outlet, which is relatively high. These results are to be expected for a plant that burns a high-sulfur coal, >3% as is the case in this study, and has an SCR in service, where, normally, about 2%–5% of the SO_2 gets converted to SO_3 in the SCR system. The chloride speciation measurements (by EPA Method 26) given in Table 18 show an average HCl level of 90 ppm (ignoring the unusually low first data point) and Cl^- level of about 2.1 ppm, which is consistent with what would be expected based on coal chloride levels.

Furthermore, these results indicate that the bulk of the chlorides species detected was essentially HCl.

Analysis of FGD Thickener Streams and ESP Ash

Ash samples collected at the ESP were analyzed for mercury content and LOI, and other samples from the FGD thickener streams were analyzed for mercury. The data from these analyses, presented in Table 19, indicate the presence of little unburned carbon and less than 10% of the coal mercury in the ash. Also shown in Table 19 are the amounts of Hg in both the solid and liquid phases of the FGD thickener streams. All solid phases are shown to have higher amounts of Hg than the liquid phases, with the Hg levels in the under- and overflow liquid phases being almost negligible. The plant limestone feed was also tested for mercury and was shown to contain an insignificant amount of mercury to be of any consequence. For example, a limestone sample taken on April 18, 2007, was determined to have about 0.004 ppm of Hg. Gypsum was also analyzed for mercury content and was determined to be a significant outlet for mercury from the system. A baseline gypsum sample from July 13, 2007, was determined to contain about 0.217 ppm of Hg on an "as-received" basis. The overall efficiency of the ESP was estimated based on the amount of ash collected on the OH filters, although this was not a compliance test. The dust-loading data are shown in Table 20, which shows that the particulate collection system at the MC4 station is very efficient.

Baseline Mercury Mass Balance

A mass balance on mercury was used to determine how it is transported throughout the MC4 station. A simplified schematic of MC4 with its key process streams is shown in Figure 12, and estimates of mass flow rates for the relevant process streams are given in Table 21. Details for estimating the mass flow rates are provided in the appendix. As indicated in Table 21, approximately 6% of the mercury was removed with the ESP ash, and most of the remainder occurred at the wet FGD. The primary path for captured mercury to leave the FGD is with the underflow solids, although some portion may be found in the thickener overflow or blowdown.

Closure percentage of the mercury mass balance was formulated according to the law of mass action as defined by the following equation:

$$\text{Closure} = \frac{\text{Hg}_{\text{out}}}{\text{Hg}_{\text{in}}} \times 100 \qquad [1]$$

A schematic of the MC4 station, Figure 12, shows that the primary output streams include bottom ash, ESP ash, stack flue gases, and thickener overflow and underflow, while the main input streams are coal and limestone inlet streams. Since the temperature at the boiler is usually high, almost all the Hg in that chamber is in the vapor phase and a negligible amount ends up in the bottom ash; this has been found to be the case in many previous studies. Also, the wet FGD underflow represents the amount of mercury that would end up in gypsum and cake wash; consequently, the amount of mercury in gypsum or cake wash does not necessarily need to be considered again in the mass balance. However, gypsum Hg levels are sometimes measured for other informational purposes. A detailed closure calculation equation becomes:

$$\text{Closure} = \frac{Hg_{ST} + Hg_{EASH} + Hg_{underflow} + Hg_{overflow}}{Hg_{coal} + Hg_{lime}} \times 100\,, \qquad [2]$$

where Hg_{ST} is the amount of Hg in stack gases, Hg_{EASH} is the amount of Hg in ESP ash, $Hg_{underflow}$ is the amount of Hg in underflow solids and liquid phases, $Hg_{overflow}$ is the amount of Hg in thickener overflow or blowdown, Hg_{coal} is amount of Hg in coal, and Hg_{lime} is the amount of Hg in limestone. Using Equation 2, the calculated closure during baseline conditions was 105.7%, which is remarkably good for a plant of the size of MC4.

Parametric Test Results

Parametric tests were completed in July of 2007. Descriptions of the tests are summarized in Table 22 and the results obtained by testing different technologies: PAC injection (ACI), scrubber additives, SEA2-T2 and a combination of ACI and scrubber additives are summarized in Table 23. It is clear from the results shown in Table 23 that ACI has little impact on mercury removal. In fact, based on the parametric test results, the application of ACI with either the B&W wet FGD additive or SEA2 resulted in lower than 90% mercury removal levels. The B&W additive alone afforded about 91% Hg removal, but a combination of ACI and the B&W additive yielded <90% Hg removal. Combining ACI with SEA2 showed even worse performance; the highest percentage of Hg removal attained was only 78% (see Table 23). Based on these results, a decision was reached by the project team, including DOE, to use the B&W wet FGD additive, which attained >90% removal at an add rate of 80 g/hr, for the long-term demonstration study.

There were substantial problems with the SEA2 systems due to plugging of the SCR system; hence, only limited tests were completed with this system. Although no additional effort was made to characterize these problems, it is believed that these difficulties may be associated with reactions of the SCR catalysts with SO_3 formed in the flue gases. This is supported, at least in part, by results from a previous study shown in Table 24, where the SCR catalyst blinding problems have a profound impact on the mercury removal efficiency; Hg removal efficiency of 43% was achieved (wet FGD to stack) with SCR in service, while bypassing the SCR system led to higher Hg removal efficiency (about 65%). The efficiency across the SCR system alone was found to be as low as 15% from baseline. This underscores the fact that to achieve any meaningful mercury emission control using these technologies with the SCR system in service, one has to effectively deal with the SCR catalyst blinding issue.

The data collected using sorbent trap are shown in Table 25 and compared with that obtained using CMMs. The results appear to be very encouraging, as the difference between CMM measurements and sorbent trap measurements is <1 $\mu g/Nm^3$ except for the cases where injection of the SEA2 additive was problematic. Using the average coal mercury concentration of 9.09 $\mu g/Nm^3$ mentioned above, a detailed analysis of these data shows that mercury removal levels measured by CMM and sorbent traps during addition of B&W additive differ by only 3%. This difference in the case of ACI and B&W additive injection is also only 4%, although it becomes, respectively, 11% and 14% when SEA2 only and ACI/SEA2 were injected. The slightly larger percentage difference in the case of SEA2 and/or SEA2/ACI can be attributed, at least in part, to the problems encountered during injection of the SEA2 additive. These results prove to be really useful and appear to suggest that, if properly designed, sorbent traps can become a relatively cheap useful alternative tool for making Hg measurements compared to CMMs.

Long-Term Demonstration Test Results

Long-term tests were conducted continuously for a period of about 1 month across the ESP and wet FGD using the B&W reemission additive with an add rate of 80 g/hr as predetermined from the results of parametric tests. During the long-term test period, daily coal samples were analyzed for Hg, Cl_2, proximate and ultimate properties, and heating value. The flue gases were monitored on a continuous basis using the CMMs. Sorbent trap measurements were also taken at the beginning and at the end of the long-term study, with the aim of finding a possible correlation between CMM data and sorbent trap data. Table 26 summarizes the results of coal analyses over this period and hourly averages of CMM measurements at the ESP and wet FGD together with the corresponding percent total Hg removal are shown graphically in Figure 13.

Average coal properties shown in Table 26 indicate that there was a slight increase in the amount of Hg in the coal, i.e., 0.1 ppm as opposed to 0.0845 ppm during the parametric test period. The coal chlorine content was also lower, the nitrogen content increased slightly, and the sulfur content remained roughly steady at about 3%. There was, however, a significant increase in the moisture content from 3.6% to about 10%, with the resultant slight decrease in the heating value. In Figure 13, hourly averaged elemental and total Hg values are plotted for both the ESP outlet (middle plot) and the FGD outlet (bottom plot) CMMs. The calculated ESP outlet-to-FGD outlet Hg removal values is also included in Figure 13 (top plot). Note that data points corresponding to periods when additive was interrupted because of maintenance have been removed. Figure 14 also shows the overall performance of the additive over the entire period and, in particular, points to some dates when the additive was interrupted. Although there are still a few spikes that indicate less than 90% removal, there are large portions of data that the efficiency is consistently above 95%. An overall average Hg removal efficiency of 91.8% was attained during the 1-month test period.

Sorbent Trap (Method 30B) Results

Method 30B sampling was conducted during the initial and final weeks of the long-term test to verify the CMM readings. During each sampling trip, four sets of sorbent trap measurements were made at the ESP outlet and FGD outlet locations. The results are summarized in Table 27 and are depicted graphically in Figures 15 and 16 for the sampling conducted during the first week of the long-term test and in Figures 17 and 18 for the sampling during the last week of the long-term test. As indicated in Table 27 and Figures 15–18, the agreement between the CMM and the corresponding sorbent trap values was good.

Additional tests were conducted on the flue gases as part of a separate project at MC4 with the aim to determine the fate of trace elements within the FGD system. Three sets of EPA Method 29 (M29) measurements were made at the ESP inlet, ESP outlet, and FGD outlet. Part of the results on the mercury content is included in this report in Table 28. These results are also in close agreement with the CMM and sorbent trap data shown in Table 27.

Mercury Content in Other Process Streams

Long-term ESP ash samples were analyzed for mercury content and LOI. The average ash mercury content was determined to be 0.0226 ppm, which is slightly lower than that detected in the baseline samples. The average LOI for the long-term samples was 0.908% and was nearly identical to the baseline values. Daily samples of the FGD thickener streams were collected and analyzed for mercury in the solid and liquid fractions. These streams include reaction tank flow into the thickener and overflow and underflow out of the thickener. The long-term average mercury concentrations for each sample are presented in Table 29. The table also presents the average solids content of each stream and the average material mass flows for the thickener. As shown in Table 29, approximately one-quarter of the incoming mass flow exited in the underflow stream, and the remaining three-quarters left as overflow.

Gypsum and limestone samples were analyzed again for mercury during the long-term test. Three samples of gypsum were collected and analyzed for mercury with a resulting "as-received" average Hg concentration of 0.208 ppm. A limestone sample from October 24, 2007, was analyzed, and the mercury content was below the detection limit of 0.01 ppm.

Long-Term Mercury Mass Balance

A mercury mass balance was calculated across MC4 at the end of the long-term test in a similar manner to the baseline mass balance. The dates chosen to compute the balance were in the last week of the long-term test period, i.e., September 24–28, 2007. This period was chosen in the hope that the system will have returned to an equilibrium condition resulting from the long-term addition of the B&W scrubber additive and to coincide with additional sampling performed under the related trace element testing project. The relevant plant process stream values are given in Table 30. Unlike baseline conditions, the plant was operating at a lower load; therefore, the stream magnitudes in Table 30 are smaller than the corresponding baseline values in Table 21.

The amount of mercury emitted from the stack during the baseline test (0.00787 lb/hr) was significantly lower during the long-term test (0.00213 lb/hr). This resulted in an improved coal-to-stack Hg removal of 94%. The long-term Hg closure was 75.8%, which is lower than was seen during baseline tests. During long-term testing, a clear drop in FGD flue gas outlet Hg was detected, but an expected concomitant rise in captured Hg leaving the FGD (e.g., in the gypsum, cake wash outlet, or chlorides blowdown) was not observed.

Some of the discrepancy may be a result of the variability observed with the mercury content of the slurry samples. Figure 19 is a plot of the mercury concentration in the liquid portion of the three FGD thickener streams. The time scale of the figure covers baseline sampling and the long-term test. During the long-term test, a change was made in the sample collection protocol, where the samples were separated into solid and liquid fractions soon after collection (denoted as "field filtering" in Figure 19). It is apparent that switching to field filtering had a dramatic effect on the amount of mercury detected in the liquid phase and that there was a significant amount of variation in these readings.

The field-filtering procedure was implemented as a protocol to satisfy the requirements of the related trace element sampling that also occurred during the long-term test. Prior to the implementation of this protocol, separated slurry samples were returned to the EERC and allowed to settle by gravity into liquid and solid fractions. For the field-filtering procedure, the slurry samples were separated with a vacuum filter soon after the samples were collected. Separate solid and liquid samples were then sent back to the EERC for analysis. Figure 19 indicates that the results from the gravity-separated samples were much lower in Hg and were more consistent. Conversely, the field-filtered samples have higher mercury contents in the liquid fractions and are much more erratic. It appears that the field-filtering left some mercury in the liquid portion that would normally settle out with time during gravity separation. An example of this is provided by the mercury content of the liquid and solid portions of the overflow slurry samples shown in Figure 20. As shown in the figure, after beginning field-filtering, there is a complete switch in liquid and solid mercury concentrations, i.e., the mercury content of the solid material goes down and was apparently detected in the liquid phase which increased in Hg concentration. This effect was not observed to the same degree with the underflow samples (Figure 21).

Impact of Mercury Mass Balance on the Plant

Because of the short-term duration of the testing compared to the operating life of the plant, truly long-term impacts of mercury control on the plant or its operations cannot be evaluated. Instead, more immediate changes were investigated. For example, MC4 currently sells its gypsum by-product for wallboard manufacture. Since the B&W additive increased mercury removal efficiency across the wet FGD, samples of the gypsum were evaluated for changes to the mercury content. The results are summarized in Table 31 for a baseline sample of the gypsum and three samples from the long-term test. Historically, Mill Creek data indicate a mercury concentration of 0.08 to 2.66 ppm in the gypsum. Therefore, the data shown in Table 31 are within the salable range.

As indicated in Table 31, the gypsum samples from the first week of the long-term test did show slightly increased mercury content, approximately 12%. However, the sample from Week 4 had an observed Hg content well below that of the baseline sample. With these few measurements, little can be concluded. In addition to the limited sample size, the gypsum samples themselves may not be totally representative of the test conditions, since gypsum from several units is combined. Gypsum from Side B of Unit 4 was mixed with gypsum from Side A and both sides of Unit 3.

CONCLUSIONS

Long-term demonstration tests of advanced sorbent enhancement additive technologies have been completed at LG&E MC4, which show that mercury removal efficiencies >90% are achievable from baseline and from coal mercury levels. Parametric tests were completed on a suite of technologies prior to the long-term study, which helped determine the best technology and optimum conditions necessary to achieve the >90% removal target on an eastern bituminous coal.

Baseline tests, followed by a suite of parametric tests, were conducted at the MC4 station in June 2007. It was found that the B&W additive added at the rate of 80 g/hr was capable of achieving >90% Hg removal from both baseline and from coal Hg levels. This technology was used for a 1-month long-term study, and the average mercury removal efficiency of 91.8% was sustained without undue complications to the plant's operation. Overall, the amount of reemission observed at MC4 was significantly lower than previously reported. PAC did not show any measurable improvement on the capture of mercury. This is not particularly surprising, since the coal has a high chlorine content, which combines with char to effect most of the elemental mercury oxidation that chlorine/PAC would be causing if the coal were low in chlorine content.

In addition to CMM and OH measurements, EPA Method 30B (sorbent trap) measurements were also obtained for comparison with the CMM and OH data. There was a surprisingly close agreement between sorbent trap and CMM results, which seems to suggest that sorbent traps are potentially a cheaper, useful alternative to CMMs for making flue gas mercury concentration measurements. Detail analysis of the coal properties revealed that the moisture content was low (<10%), but chlorine and sulfur levels were high (>1100 ppm and >3%, respectively). The nitrogen content was about 1.5% on average, and the heating value was about 12,000 Btu. These values are consistent with what is known about typical eastern bituminous coals.

The tests were carried out on Side B of MC4, and a baseline mercury removal of 78% was observed, with approximately 6% of the mercury entering in the coal captured across the ESP. The remaining removal occurred across the wet FGD, where the average outlet mercury concentration during baseline was 1.99 $\mu g/Nm^3$ dry at 3% O_2. The closure for the long-term Hg balance was not as good as the baseline calculation, i.e., 75.8% as opposed to 105.4% during baseline testing. The long-term mass balance clearly showed a reduction in Hg emissions at the stack but not with an expected concomitant rise in the amount of captured Hg leaving the FGD through gypsum, cake wash outlet, or chlorides blowdown. The high degree of variability observed in the Hg content of the FGD slurry samples appears to be part of the reason for the poor Hg mass balance, especially for the long-term study. However, with the B&W scrubber additive in operation, the long-term Hg mass balance indicated a coal-to-stack removal of 94% and the average FGD outlet mercury concentration during the long-term test was 0.65 $\mu g/Nm^3$ dry at 3% O_2.

The long-term mercury control test had little impact on the gypsum mercury content. However, in theory, this should be the primary outlet for the additional captured mercury. This observation is probably due to the composite nature of the gypsum samples. Although the study period was relatively short compared to the plant's lifetime for any conclusions on the impact of Hg balance on the plant's operation to be drawn, our measurements indicate very low Hg levels in gypsum by-product sold to a wall boarding company. Measurements obtained during the 1-month application of the B&W reemission additive show a reduction in the gypsum Hg content of at least 10% relative to previous levels reported by the plant. Hence, the gypsum continues to be salable in quality, especially after the application of the B&W scrubber additive.

At HAW5, results of the parametric tests revealed that two possible technologies are capable of achieving more than 90% mercury removal from baseline and from coal mercury levels. These include addition of PAC (2 lb/Macf) in combination with Cl_2 (500 ppm) and the DARCO Hg-LH additive (3 lb/Macf), which showed performances of 94% and 93%, respectively, from coal mercury levels (93% and 90%, respectively, from baseline mercury levels). Furthermore, addition of PAC (322 lb/hr) in conjunction with Cl_2 (1200 ppm) and the DARCO Hg-LH (2 lb/Macf) each afforded 89% removal from coal mercury levels, and each of these was only about 3% short of 90% removal from baseline.

Substantial SCR catalyst blinding was observed at the Hawthorn station, which led to lower oxidized elemental mercury levels. A limited number of sorbent trap measurements also showed reasonable agreement with CMM data. Detail analysis of the coal samples showed a relatively high moisture content (~20%) and very low chlorine, sulfur, and nitrogen levels (~15 ppm, <0.5% and <1%, respectively). Because of the higher amount of moisture, the average heating value was about 10,000 Btu. However, these properties are within the range that can be expected for typical PRB subbituminous coals.

Parametric tests that were carried out seem to indicate that long-term study can be conducted without any foreseeable problems. More importantly, the tested technologies have demonstrated that it is possible to achieve >90% Hg removal from baseline and from coal levels.

REFERENCES

1. Center for Air Toxic Metals. *Center for Air Toxic Metals Final Technical Report Volume IV*; Final Technical Report (Oct 15, 1999 – Sept 30, 2004) for U.S. Environmental Protection Agency Assistant Agreement R 827649-01; Energy & Environmental Research Center: Grand Forks, ND, Dec 2004.

2. Sondreal, E.A.; Benson, S.A.; Pavlish, J.H.; Galbreath, K.C.; Zygarlicke, C.J.; Thompson, J.S.; McCollor, D.P; Crocker, C.R.; Lillemoen, C.M.; Mann, M.D.; Jensen, R.R.; Weber, G.F. *Center for Air Toxic Metals Final Technical Report Volume 3*; Final Technical Report for U.S. Environmental Protection Agency Assistant Agreement R824854; Energy & Environmental Research Center: Grand Forks, ND, Sept 2000.

3. Pavlish, J.H.; Benson, S.A.; Zygarlicke, C.J.; Erickson, T.A.; Galbreath, K.C.; Schelkoph, G.L.; O'Leary, E.M.; Timpe, R.C.; Anderson, C.M. *Center for Air Toxic Metals Final Technical Report Volume 2*; Final Technical Report for U.S. Environmental Protection Agency Contract No. CR823173; EERC Publication 98-EERC-03-03; Energy & Environmental Research Center: Grand Forks, ND, April 1998.

4. Benson, S.A.; Pavlish, J.H.; Erickson, T.A.; Katrinak, K.A.; Miller, S.J.; Steadman, E.N.; Zygarlicke, C.J.; Dunham, G.E.; Pflughoeft-Hassett, D.F.; Galbreath, K.C. *Center for Air Toxic Metals Final Technical Report Volume 1*; Final Technical Report for U.S. Environmental Protection Agency Contract No. CR821518-01; Energy & Environmental Research Center: Grand Forks, ND, Dec 1995.

5. Benson, S.A.; Crocker, C.R.; Galbreath, K.C.; Gunderson, J.R.; Holmes, M.J.; Laumb, J.D.; Mackenzie, J.M.; Olderbak, M.R.; Pavlish, J.H.; Yan, L.; Zhuang, Y. *Pilot- and Full-Scale Demonstration of Advanced Mercury Control Technologies for Lignite-Fired Power Plants*; Final Report for U.S. Department of Energy National Energy Technology Laboratory Cooperative Agreement No. DE-FC26-03NT41897; EERC Publication 2005-EERC-02-05; Energy & Environmental Research Center: Grand Forks, ND, Feb 2005.

6. Benson, S.A.; Mackenzie, J.M.; McCollor, D.P.; Galbreath, K.C. *Mercury Control Technologies for Electric Utilities Burning Subbituminous Coals*; Draft Multiclient Final Report, JV Task 73 (Jan 2, 2004 – June 30, 2005), for U.S. Department of Energy Cooperative Agreement No. DE-FC26-98FT40321; Energy & Environmental Research Center: Grand Forks, ND, June 2005.

7. Benson, S.A.; Holmes, M.H.; McCollor, D.P.; Mackenzie, J.M. *Large-Scale Mercury Control Technology Testing for Lignite-Fired Utilities – Oxidation Systems for Wet FGD*; Technical Progress Report (April 1 – June 30, 2005) for the U.S. Department of Energy National Energy Technology Laboratory under DOE NETL Cooperative Agreement DE-FC26-03NT41991; Energy & Environmental Research Center: Grand Forks, ND, July 2005.

8. Holmes, M.J.; Pavlish, J.H.; Thompson, J.S.; Wocken, C.A. *Enhancing Carbon Reactivity in Mercury Control in Lignite-Fired Systems*: Technical Progress Report for (April 1–June 30, 2005) for the U.S. Department of Energy National Energy Technology Laboratory Cooperative Agreement DE-FC26-03NT41989; Energy & Environmental Research Center: Grand Forks, ND, Aug 2005.

9. Holmes, M.J.; Pavlish, J.H.; Thompson, J.S.; Wocken, C.A. *Enhancing Carbon Reactivity in Mercury Control in Lignite-Fired Systems;* Technical Progress Report for (July 1–Sept 30, 2004) for the U.S. Department of Energy National Energy Technology Laboratory Cooperative Agreement DE-FC26-03NT41989; Energy & Environmental Research Center: Grand Forks, ND, Nov 2004.

10. Olson, E.S.; Crocker, C.R.; Benson, S.A.; Pavlish, J.H.; Holmes, M.J. Surface Compositions of Carbon Sorbents Exposed to Simulated Low Rank Coal Flue Gases. *J. Air Waste Manage. Assoc*. **2005**, 747–754.

11. U.S. Environmental Protection Agency. *Information Collection Request*, 1999.

12. ASTM D6784-02, “Standard Test Method for Elemental, Oxidized, Particle-Bound and Total Mercury in Flue Gas Generated from Coal-Fired Stationary Sources (Ontario Hydro method),” ASTM International, West Conshohocken, PA, www.astm.org.

APPENDIX A

ESTIMATION OF MASS FLOW RATES

ESTIMATION OF MASS FLOW RATES

This appendix describes the assumptions made in the estimation of mass flow rates of the various process streams used to calculate the baseline and long-term mercury mass balances. These calculations are demonstrated using data from the long-term tests.

Coal In: Coal feed rate during sampling was recorded in a plant-provided data file. The average coal feed rate for the period September 24–28, 2007, was 362,707 lb/hr, the average coal moisture was 10.1%, and the computed dry coal feed was 326,000 lb/hr.

Flue Gas Flow: The average flue gas flow rate was calculated from the F_d factor determined from the coal ultimate analysis. The coal Fd factor and heating value were 11,007 dscf/MMBtu and 11,253 Btu/lb (as-received), respectively. The flow determination is given by:

$$362{,}707\,\text{lb coal/hr} \times 11{,}253\,\text{Btu/lb coal}\,\frac{11{,}007\,\text{dscf}\,(21-0)}{1{,}000{,}000\,\text{Btu}(21-3)} = 524 \times 10^5 \text{ dscf/hr at } 3\%\ O_2$$

ESP Ash Out: The quantity of ash produced by Unit 4 was estimated using the measured ash content and the recorded coal feed rate. The amount of the total ash reaching the ESP was assumed to be 80%, with the remaining 20% distributed as bottom ash. The average coal ash content was 10.2% (as received), and about 80% of it was reaching the ESP as fly ash, which corresponds to an ESP collection efficiency of 99.5%. Hence the ESP ash flow rate was determined as:

$$362{,}707\,\text{lb coal/hr} \times 0.102\,\text{lb ash/lb coal} \times \frac{0.8\,\text{ESP ash}}{\text{Total ash}} \times \frac{0.995\,\text{captured ESP ash}}{\text{Total ESPash}} = 29{,}400 \text{ lb/hr}$$

Limestone In: The limestone consumption rate was not directly measured; therefore, the rate was estimated by calculating the steady-state amount of limestone needed to neutralize the sulfur present in the coal according the following equation

$$CaCO_3 + S + \frac{1}{2}O_2 + 2H_2O \rightarrow CO_2 + CaSO_4 \cdot 2H_2O \qquad \text{[A-1]}$$

XRF analysis of the limestone samples indicated that they were approximately 94% calcium carbonate ($CaCO_3$). Therefore, for every pound of sulfur entering with the coal, there are approximately 100.09/32.06 = 3.12 pounds of calcium carbonate consumed for neutralization or 3.12/0.94 = 3.32 pounds of the tested limestone. With the coal sulfur content of 3.12% (as received), the flow rate was determined as:

$$362{,}707\,\text{lb coal/hr} \times \frac{3.12\,\text{lb Sulfur}}{100\,\text{lb coal}} \times 3.32\,\text{lb limestone/lb Sulfur} = 37{,}600 \text{ lb limestone/hr}$$

Gypsum Out: Gypsum production rate was not recorded; instead, an estimate of the rate was calculated based on the required stoichiometry of gypsum formation reactions shown in Equation

A-1. The molar ratio between sulfur in the coal and gypsum ($CaSO_4 \cdot 2H_2O$) is 1:1. Assuming that approximately 94% of the sulfur in the coal was captured and converted to gypsum, then for every pound of sulfur entering the coal, there were (0.94)172.17/32.06 = 5.05 pounds of gypsum produced, for an estimated flow rate of:

$$362,707\,\text{lb coal/hr} \times \frac{3.12\,\text{lb Sulfur}}{100\,\text{lb coal}} \times 5.05\,\text{lb gypsum/lb Sulfur} = 57{,}100\ \text{lb gypsum/hr}$$

The gypsum samples gathered from the plant were composed of gypsum from four individual scrubber units (presumably the two sides of Unit 4 and the two sides of Unit 3), not just the test side of Unit 4. Therefore, any change in gypsum composition due to the control technology was diluted by these other gypsum streams.

Underflow: To define the magnitude of this stream, the percentage of solids present in the underflow were assumed to be equal to the rate of gypsum production. During the long-term tests, the flow rates were given by long-term underflow solids of 29.1%, for underflow solids rate of 57,100 lb/hr. Underflow liquids is given by:

$$\frac{57{,}100(1-0.291)}{0.291} = 139,000\,\text{lb/hr}$$

Blowdown Outlet Flow: No indication of blowdown flow was provided. Instead, an estimate was based on a chloride mass balance of the entire plant. The extensive chloride data needed for a mass balance were collected during a related trace element sampling study that was performed during the long-term test. The information is given below:

Cl entering in coal = 333 lb Cl/hr
Cl entering with limestone = 1.75 lb Cl/hr
Cl leaving with ESP ash = 0.613 lb Cl/hr
Cl leaving in the flue gas = 8.75 lb Cl/hr
Cl leaving with gypsum = 3.71 lb Cl/hr
Cl leaving with cake wash = 272 lb Cl/hr

The difference of approximately 49.7 lb Cl/hr was assumed to be removed with the blowdown stream. The blowdown stream has the same composition as the thickener overflow stream.

Hence:
Averaged blowdown (overflow) solids = 4.78%
Averaged chloride content of blowdown (overflow) liquids = 1950 ppm
Averaged chloride content of blowdown (overflow) solids = 171 ppm

The chloride mass balance is summarized as in the following equation:

$$\frac{(1-0.0478)1950\dot{m}_{\text{Blowdown}} + (0.0478)171\dot{m}_{\text{Blowdown}}}{1,000,000} = 49.7\ \text{lb Cl/hr}, \qquad \text{[A-2]}$$

which results in a total blowdown flow of 26,700 lb/hr. Solving for the solid and liquid mass flow rates of the blowdown stream results in:

Blowdown solids = (0.0478)26,600 = 1270 lb/hr, and
Blowdown liquids = (1 – 0.0478)26,600 = 25,400 lb/hr

APPENDIX B

LONG-TERM DEMONSTRATION OF SORBENT ENHANCEMENT ADDITIVE TECHNOLOGY FOR MERCURY CONTROL – SAN MIGUEL

LONG-TERM DEMONSTRATION OF SORBENT ENHANCEMENT ADDITIVE TECHNOLOGY FOR MERCURY CONTROL

Final Report

(for the period November 1, 2008, through August 31, 2009)

Prepared for:

Joseph Eutizi

San Miguel Electric Cooperative, Inc.
PO Box 280
Jourdanton, TX 78026

Prepared by:

Nicholas B. Lentz
John P. Kay
Jason D. Laumb

Energy & Environmental Research Center
University of North Dakota
15 North 23rd Street, Stop 9018
Grand Forks, ND 58202-9018

2009-EERC-09-07 September 2009

EERC DISCLAIMER

LONG-TERM DEMONSTRATION OF SORBENT ENHANCEMENT ADDITIVE TECHNOLOGY FOR MERCURY CONTROL

ABSTRACT

In the United States, testing has been under way at electric coal-fired power plants to find viable and economical mercury control strategies to meet pending regulations. San Miguel Electric Cooperative (SMEC) engaged the Energy & Environmental Research Center (EERC) through a request for proposal to perform research tests to evaluate sorbent-based technologies at its coal-fired San Miguel Generating Station to identify possible technology options that could be used by SMEC to meet the mercury reduction requirements of future U.S. federal standards and to evaluate a scrubber additive designed to reduce reemission. The goal of the testing was to target a mercury removal of ≥90% and to evaluate a scrubber additive and determine its effects on reemission.

The EERC has successfully field-tested several sorbent-based technologies in previous projects that offer promise and potential to achieve a target removal of ≥90%. Based on these field test results, yet recognizing that fuel type and plant operating conditions affect mercury capture significantly, the EERC proposed research tests to evaluate potential sorbent-based technologies provided by Norit Americas and the EERC that could potentially meet SMEC's mercury control objectives. Over the period of late April through mid-May 2009, the EERC tested injection of both treated and untreated activated carbon provided by Norit Americas and sorbents and sorbent enhancement additives provided by RLP Energy. A scrubber additive provided by Babcock & Wilcox was also tested. Tests were performed at San Miguel Unit 1 (450 MW) and included injection at the inlet of the air heater (temperature of 708°F). The test coal was a Texas lignite fuel with an average moisture content of 31.10%, an ash content of 22.35%, a heating value of 5281 Btu/lb, a sulfur content of 2.67%, and a mercury concentration of 0.193 ppm, all reported on an as-received basis.

Mercury concentrations were tracked with continuous mercury monitors (CMMs) at the electrostatic precipitator (ESP) scrubber inlet (EERC-provided), and stack (plant CMM) of San Miguel Unit 1, and a dry sorbent trap method was used to take samples periodically to measure mercury concentrations at each of the CMM sampling locations described above. A limited number of Ontario Hydro (OH) measurements were also conducted. Removal efficiencies were calculated from mercury-in-coal values to scrubber inlet and stack mercury concentrations in order to obtain removals across the ESP and stack removals. Sorbent trap samples taken at each sampling location were found to be consistent with CMM and OH data.

A maximum mercury removal of 81.7% was achieved with the SF11-SB11 RLP technology combination at SF11 and SB11 injection rates of 80 lb/hr and 3.5 lb/Macf (at 300°F), respectively. An injection rate of 3.5 lb/Macf for DARCO® Hg-LH and 4.0 lb/Macf for DARCO® Hg resulted in mercury removals of 73.4% and 71.5%, respectively. Scrubber reemission was observed during sorbent injection and had a significant effect on coal-to-scrubber outlet mercury removal values. The B&W scrubber additive had little to no effect on scrubber reemission.

TABLE OF CONTENTS

LIST OF FIGURES ii

LIST OF TABLES ii

EXECUTIVE SUMMARY iii

INTRODUCTION 1
  Project Participants 2

BACKGROUND 2

GOALS AND OBJECTIVES 5

DESCRIPTION OF THE TEST UNIT 6

TEST PLAN 7
  ACs from Norit Americas 7
  Sorbents and SEAs from RLP Energy 8
  Flue Gas Sampling 8
  Solids Sampling and Analysis 10
  Plant Data 11

TEST EQUIPMENT 11

RESULTS AND DISCUSSION 11
  Mercury in Coal 12
  Baseline Conditions 14
  Parametric Tests 16
    DARCO Hg 16
    DARCO Hg-LH 17
    RLP Energy Sorbents and SEAs 17
    B&W Scrubber Additive 21

CONCLUSIONS 22

REFERENCES 22

PLANT OPERATING DATA ..... Appendix A

SAMPLING CALCULATIONS ..... Appendix B

COAL DATA ..... Appendix C

CONTINUOUS MERCURY MONITOR, ONTARIO HYDRO, AND SORBENT TRAP DATA ..... Appendix D

LIST OF FIGURES

1 Chemisorption model for mercury–flue gas interactions with AC sorbents 3

2 Pilot-scale data showing the mercury removal of plain and treated/enhanced carbon on an ESP-only configuration 4

3 San Miguel Unit 1 schematic showing injection and sampling locations 7

4 Comparison of day-to-day mercury concentrations in the test coal 13

5 Inlet flue gas mercury concentrations calculated from combustion calculations 13

6 Scrubber inlet baseline mercury measurement data 15

7 Scrubber inlet mercury removal percentages during DARCO Hg injection 16

8 Scrubber inlet mercury removal percentages during DARCO Hg-LH injection 17

9 Scrubber inlet mercury removal results during the injection of SF11 into the furnace 18

10 Scrubber inlet mercury removal results during the injection of SF11 into the furnace and the injection of SB11 into the AH inlet 19

11 Scrubber inlet CMM data obtained during the SF11–SB11 extended test 20

12 Scrubber inlet CMM data obtained during the SF11–SB26 extended test 20

13 CMM mercury removal results across the ESP during the injection of the scrubber additive 22

LIST OF TABLES

1 Mercury Removal as a Function of Coal Type and Plant Configuration 3

2 Average Coal Values for the Test Coal 8

3 Calculated Hg Flue Gas Concentrations Based on Hg Coal Concentrations 12

4 Baseline OH Data 14

5 Effects of Scrubber Additive on Mercury Removal Across the Scrubber 21

LONG-TERM DEMONSTRATION OF SORBENT ENHANCEMENT ADDITIVE TECHNOLOGY FOR MERCURY CONTROL

EXECUTIVE SUMMARY

In the United States, testing has been under way at electric coal-fired power plants to find viable and economical mercury control strategies to meet future regulations. Previous testing at San Miguel Electric Cooperative (SMEC) conducted in May–June 2008 indicated that scrubber reemission had a significant impact on coal-to-stack mercury removal. Because of these results, SMEC engaged the Energy & Environmental Research Center (EERC) to perform research tests to evaluate sorbent-based technologies with and without scrubber additives to determine the impact of scrubber reemission on mercury removal and determine the effectiveness of scrubber additives on reducing mercury reemission to reach a mercury removal of ≥90%.

The single 450-MW (gross) unit at the San Miguel Generating Station is equipped with an electrostatic precipitator (ESP) for particulate control and a wet flue gas desulfurization system to reduce SO_x emissions. The EERC has successfully field-tested several sorbent-based technologies in previous projects that offer promise and potential to achieve a target removal of ≥90%. Based on these field test results, yet recognizing that fuel type and plant operating conditions affect mercury capture significantly, the EERC proposed research tests to evaluate potential sorbent-based technologies provided by Norit Americas and RLP Energy that could potentially meet SMEC's mercury control objectives. A Babcock & Wilcox (B&W) scrubber additive was also proposed to determine its effectiveness at reducing scrubber reemission. Over the period of May 2009, the EERC tested injection of both treated and untreated activated carbon (AC) provided by Norit Americas as well as sorbents and sorbent enhancement additives (SEAs) provided by RLP Energy. Tests were performed at San Miguel Unit 1 (450 MW) and included injection at the inlet of the air heater (AH) (temperature of 708°F) as well as furnace injection of RLP Energy SEAs.

The coal combusted during this project was a Texas lignite which is mined in the land adjacent to the power plant and transported to the plant via dump trucks. Table ES-1 presents the average coal properties on an as-received basis.

Mercury concentrations were tracked with continuous mercury monitors (CMMs) at the scrubber inlet and stack (plant CMM) of San Miguel Unit 1, Ontario Hydro (OH) sampling at the scrubber inlet and stack, and a dry sorbent trap (ST) method at the ESP inlet, scrubber inlet, and stack. Overall mercury removal efficiencies were calculated from mercury-in-coal values to stack mercury measurements. Each measurement technique correlated well with the other techniques conducted at the same location and typically exhibited less than a 10% variation.

Baseline and parametric tests were completed over a 1-month period while combusting the coal noted above. To determine baseline emissions and technology effectiveness, overall mercury percent removals were calculated using mercury-in-coal values compared to stack mercury measurement values. Mercury percent removals were also determined for removal

Table ES-1. Average Coal Values for the Test Coal

Parameter	As-Received Basis Average[a]	Std. Dev
Hg, ppm	0.193	0.020
Total Halogens, ppm	563	58
Br, ppm	3.52	0.67
Proximate Analysis, wt%		
Moisture	31.10	0.92
Volatile Matter	24.90	0.49
Fixed Carbon	21.64	1.01
Ash	22.35	1.74
Ultimate Analysis, wt%		
Hydrogen[b]	2.87	0.10
Carbon	30.77	1.11
Nitrogen	0.46	0.02
Sulfur	2.67	0.10
Oxygen[b]	9.77	0.57
Heating Value, Btu/lb	5281	192

[a] Average values are based on 17 samples.

[b] Moisture contribution removed.

across the ESP using mercury-in-coal values compared to the scrubber inlet CMM. Baseline results with no sorbent injection showed a native mercury removal of 39.4%, with most of the mercury removal occurring across the scrubber.

Parametric testing entailed the injection of sorbents into the AH inlet (temperature of 708°F). Two Norit Americas products, a standard AC, DARCO® Hg and a brominated treated AC, DARCO® Hg-LH were evaluated for mercury control at the San Miguel Generating Station. Select proprietary RLP Energy sorbents and SEAs were also tested. The B&W scrubber additive was tested with DARCO Hg-LH. Parametric tests of 0.5–4 hours in duration were performed using these test materials by varying the injection rates and evaluating their effectiveness to capture mercury, as measured by the scrubber outlet and stack mercury concentrations. Mercury removal efficiencies for these options varied from 63.2% to 81.7%.

Figure ES-1 displays the maximum mercury removals obtained with DARCO, DARCO Hg-LH, and RLP Energy's SF11–SB11 technology. When DARCO Hg was injected at 4.0 lb/Macf, a mercury removal of 71.5% was obtained from a ST measurement. When DARCO Hg-LH was injected at 3.5 lb/Macf, a mercury removal of 73.4% was obtained. The RLP SF11–SB11 technology yielded a mercury removal of 81.7% at SF11 and SB11 injection rates of 0.56 and 3.5 lb/Macf, respectively.

Baseline OH data confirmed that scrubber reemission was occurring even without sorbent injection. The average baseline Hg^0 entering the scrubber based on OH data was 19.06 μg/dNm^3 at 3% O_2. The corresponding average stack OH data showed a Hg^0 concentration of 21.94 μg/dNm^3 at 3% O_2. This shows a 2.88 μg/dNm^3 increase in Hg^0 concentration across the scrubber, which is indicative of scrubber reemission.

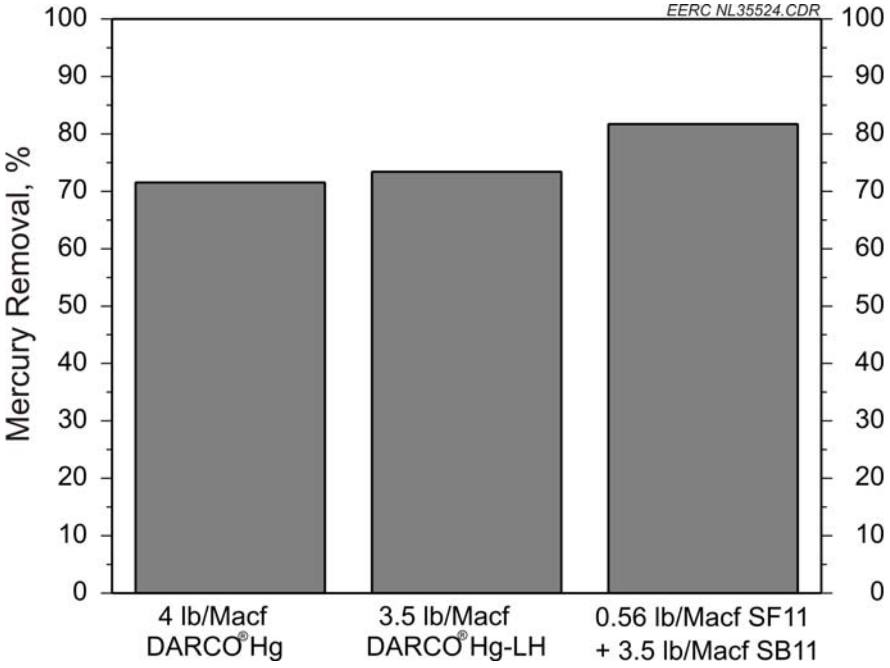


Figure ES-1. Maximum mercury removals obtained with each technology tested. The lb/Macf injection rates are calculated based on the ESP inlet temperature of 300°F.

The B&W scrubber additive had little effect on scrubber reemission at SMEC. Mercury removals during the injection of DARCO Hg-LH were consistent with and without the scrubber additive being injected. Parametrically increasing the scrubber additive rate from 600 lb/hr to 1000 lb/hr to 1400 lb/hr had no significant effect on mercury removal. Paired scrubber inlet and stack OH measurements collected at a DARCO Hg-LH injection rate of 3.0 lb/Macf and a scrubber additive rate of 1400 lb/hr provided Hg^0 concentrations of 10.86 $\mu g/dNm^3$ at 3% O_2 and 14.63 $\mu g/dNm^3$ at 3% O_2, respectively. The increase in Hg^0 concentration across the scrubber demonstrated that scrubber reemission was occurring even when the scrubber additive was being injected.

LONG-TERM DEMONSTRATION OF SORBENT ENHANCEMENT ADDITIVE TECHNOLOGY FOR MERCURY CONTROL

INTRODUCTION

In the United States, testing has been under way at electric coal-fired power plants to find viable and economical mercury control strategies to meet the requirements of the Clean Air Act Amendments. Despite the fact that the U.S. Clean Air Mercury Rule was recently overturned, state limits are generally quite stringent and call for greater limits than those that were expected at the federal level. It is also likely that upcoming federal mercury regulations will adopt a maximum achievable control technology (MACT) standard. The Energy & Environmental Research Center (EERC) has been fully involved in these discussions and in technology development and testing efforts for over 15 years. The technology that presently holds the most promise to meet U.S. regulations for mercury control is injection of activated carbon (AC) into the flue gas stream—both with and without enhancement additives. San Miguel Electric Cooperative (SMEC) engaged the EERC to perform additional research tests to evaluate sorbent-based technologies and a scrubber additive technology at SMEC's coal-fired San Miguel Generating Station to identify possible technology options that could be used by SMEC to meet the mercury reduction requirements of the future U.S. federal standards, with mercury removals targeted at ≥90%.

To achieve this reduction goal, an intensive research project was initiated in April 2009 to perform mercury sampling and measurement while evaluating a number of mercury control technologies and a scrubber additive technology at the San Miguel Generating Station, which is located near Christine, Texas, and owned/operated by SMEC. The single 450-MW (gross) unit at San Miguel is equipped with a cold-side electrostatic precipitator (ESP) for particulate control, and a wet flue gas desulfurization (WFGD) system to reduce SO_x emissions. The EERC has successfully field-tested several sorbent-based technologies in previous projects that offer promise and potential to achieve a target removal of ≥90%. Based on these field test results, yet recognizing that fuel type and plant operating conditions affect mercury capture significantly, the EERC proposed research tests to evaluate potential sorbent-based technologies provided by Norit Americas and RLP Energy that could potentially meet SMEC's mercury control objectives. A scrubber additive was also provided by Babcock & Wilcox (B&W) to evaluate its effectiveness in reducing mercury reemission across the scrubber. Over the period of May 2009, the EERC tested injection of both treated and untreated AC provided by Norit Americas as well as sorbents and sorbent enhancement additives (SEAs) provided by RLP Energy. Tests were performed at San Miguel Unit 1 (450 MW) and included injection at the inlet of the air heater (AH) (temperature of 708°F).

Baseline and parametric tests were completed over a 1-month period while combusting the coal noted above. To determine baseline emissions and technology effectiveness, mercury removal percentages were calculated using mercury-in-coal values compared to stack (continuous mercury monitor [CMM] and sorbent traps[STs]) and scrubber outlet (CMM, ST, and Ontario Hydro [OH]) values.

Project Participants

To execute the project, several organizations were involved, requiring a collaborative approach. The roles of each project participant are briefly described below:

- SMEC assembled the project team and contracted organizations to perform the research project. SMEC also managed corporate and plant activities, communication, and interfaced with and directed the project team.

- San Miguel Generating Station, owned and operated by SMEC, served as the host site for testing and operated the stack CMM.

- The EERC, a U.S.-based research, development, demonstration, and commercialization research organization, was contracted by SMEC to serve as project lead. In this capacity, the EERC oversaw and managed the research program; provided test and measurement equipment; and coordinated and performed tests, data reduction, and reporting.

- Norit Americas, Inc., a commercial provider of ACs, provided both treated and untreated ACs and two portable sorbent injection systems.

- RLP Energy, Inc., a commercial vendor that supplies long-term equipment, materials, and services to power utilities, provided SEA and proprietary test materials and front-end injection equipment.

- B&W, Inc., a commercial vendor of utility-related equipment, construction, and scrubber additives, provided a scrubber additive to test in the scrubber at SMEC.

BACKGROUND

Since the U.S. Environmental Protection Agency (EPA) announced its intention to regulate mercury in 2000, utilities have been seeking to develop and test possible technology options for mercury control. The U.S. government has provided funds, as have many utilities, to assess various strategies that would provide the best economics with optimal mercury control.

Although several mercury control technologies have been developed and tested at various scales, sorbent-based technologies, specifically AC technologies, have been identified as the most mature, consistent, and economical approach for mercury removal. During early testing in the United States, it became apparent that coal type and plant configuration were the two biggest factors affecting the possible removal of mercury, as illustrated in Table 1.

In the past, low-chlorine coals (below 500 ppm) were considered to be most problematic and challenging for mercury control. This is partly because the lack of chlorine results in a low ratio of oxidized mercury in the flue gas compared to the total mercury concentration. Through

Table 1. Mercury Removal as a Function of Coal Type and Plant Configuration

Control Tech. (no. plants)	Bituminous	Subbituminous	Lignite	All Coals
Cold-Side ESP (640)	30–40	0–20	0–10	0–40
Cold-Side ESP + WFGD (129)	60–80	15–35	0–40	0–80
Dry FGD + Cold-Side ESP (4)	35–50	10–35	0–10	0–50
Fabric Filter (58)	40–90	20–75	0–10	0–90
Fabric Filter + WFGD (15)	75–95	30–75	10–40	10–95
Dry FGD + Fabric Filter (37)	65–95	20–40	0–20	0–95
Coal Cleaning	20–40	?	?	0–40

* Typical values based on EPA notice of data availability, information collection request data, field tests, and observations. Some values are based on single data points and may not reflect removal for all plants.

extensive research, the EERC has developed a complex mercury–sorbent–flue gas interaction model, shown in Figure 1, that shows the role and impact that various flue gas components have on chemisorption (1).

The EERC model further shows that mercury oxidation (whether in the gas phase or on/within the carbon structure) must occur before the basic sites on the carbon can chemisorb the mercury. The basis of this model provides much insight into why the mercury must be oxidized, how to enhance mercury oxidation on the carbon through the use of SEAs, and why and how NO_x and SO_x (SO_2 and SO_3) impact the carbon's ability to capture mercury. For example, for low-chlorine coals that produce predominantly elemental mercury, an oxidant such as a halogen is needed to promote oxidation of the mercury on/within the carbon, which is then

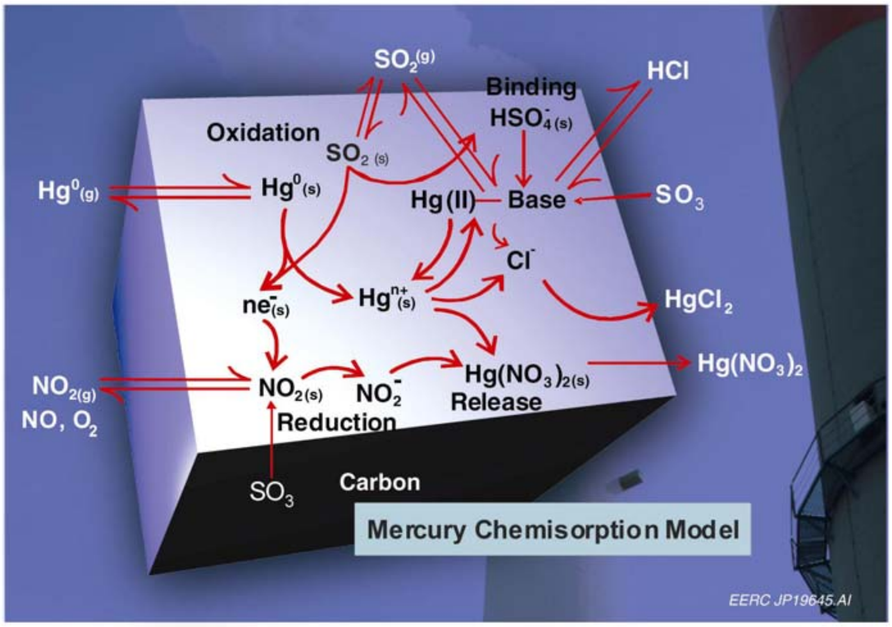


Figure 1. Chemisorption model for mercury–flue gas interactions with AC sorbents.

subsequently captured on basic sites within the carbon structure. In contrast, for coals that produce high amounts of SO_3, the SO_3 will bind to these basic sites preferentially, limiting the sites available for mercury chemisorption. This is of significant importance when SO_3 injection is used to condition fly ash to improve ESP collection.

For the reasons stated above, plain (untreated) ACs have often yielded poor capture for plants burning low-halogen coals, such as lignite and Powder River Basin coals. In these cases, the carbon has low reactivity unless SEAs or treated ACs are used. However, results for both approaches are very site-specific, as several field tests have shown varying rates of effectiveness depending on plant configuration, operating conditions, and coal type (or blends of coal).

Several economic analyses have shown that the AC cost is the largest ongoing factor when AC injection is used as a mercury control strategy. Additives and/or treatments, as shown in Figure 2, can be used to lower the total amount of injected material, which can lessen the balance-of-plant impacts on air pollution control devices while often promoting mercury capture at a reduced price. If these technologies can lessen the total amount of AC injected, utility by-product sales may also be maintained, thereby preserving a valuable revenue stream and lessening the amount of material to be landfilled.

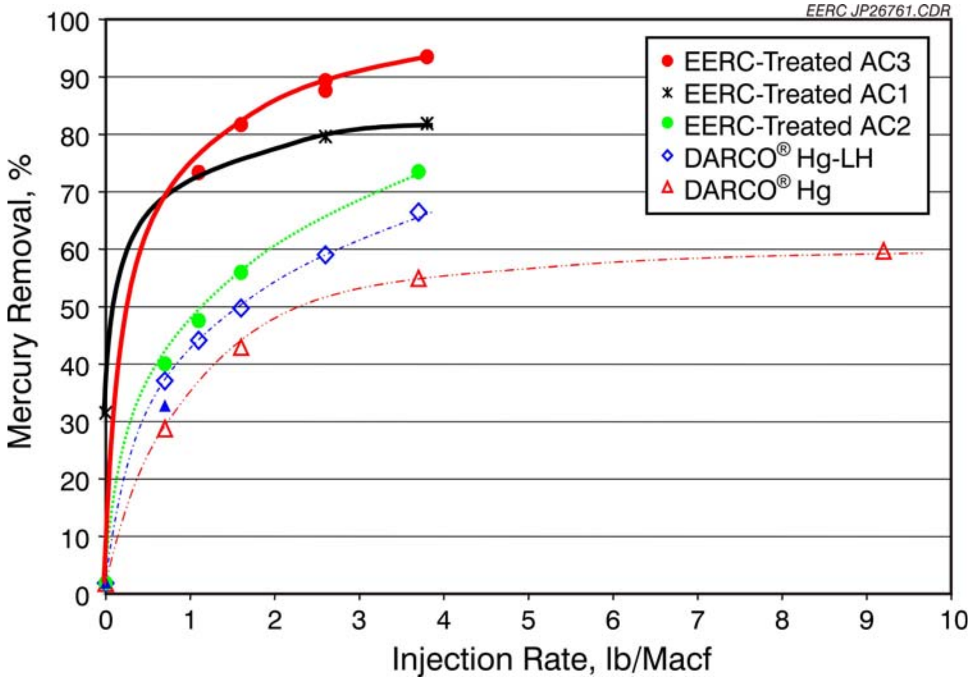


Figure 2. Pilot-scale data showing the mercury removal of plain and treated/enhanced carbon on an ESP-only configuration.

GOALS AND OBJECTIVES

The goal of the project was to identify and evaluate additional technology options that could be used by SMEC to meet the mercury reduction requirements of future U.S. regulations, with mercury removals targeted at ≥90%, as well as determine the effectiveness of a scrubber additive to reduce mercury reemission across the scrubber. The objectives of the field testing activities were to gather data (technology effectiveness, preliminary economics, etc.) to guide future test and installation decisions and support the development of SMEC's mercury control strategy.

The coal burned at San Miguel presents a challenge to control mercury on several fronts. First, the coal mercury concentration exhibits a high degree of variability on a daily and hourly basis. Secondly, the high ash content of the coal makes analytical measurements challenging. Finally, the high volume of coal being combusted, approximately 450–480 ton/hr, results in high lb/hr sorbent injection rates compared to plants of similar megawatt size. The high lb/hr injection rates increase the cost per pound for mercury captured.

To meet these challenges and the overall project goal, the EERC and SMEC identified the following pretest objectives and activities to adequately prepare for the test program:

- The test team determined the best injection schemes by performing flow modeling in order to design injection lances, splitters, and necessary ports for good dispersion of the injected sorbents.

- A site-specific test plan (SSTP) that included baseline and parametric testing was prepared by the EERC with the guidance and assistance of SMEC.

- A temporary sorbent injection system was installed to allow testing at the AH inlet location.

Testing activities included the following objectives for the San Miguel Generating Station:

- A SSTP was prepared, updated, and submitted to all team members as needs evolved over the course of testing.

- The injection location was upstream of the existing cold-side ESP on this unit, with the planned primary location upstream of the AH, which allowed for increased residence time and maximized sorbent effectiveness.

- To obtain stack mercury concentration data for Unit 1, SMEC's stack CMM was utilized.

- An additional CMM was installed by the EERC at the scrubber inlet.

- ST and OH testing were used to verify the CMM results.

- On-site mercury analysis of ST and OH samples was conducted in the EERC's mobile laboratory in order to obtain rapid feedback to evaluate mercury removals and to support ongoing testing decisions.

- Coal and ash samples were obtained and analyzed off-site to support evaluation of mercury removals.

- Quality measures were implemented to ensure accurate measures of mercury in coal, fly ash, and flue gas to accurately evaluate mercury removal effectiveness.

DESCRIPTION OF THE TEST UNIT

The San Miguel Generating Station, owned and operated by SMEC, comprises one 450-MW unit and is located near Christine, Texas. The physical plant address is as follows:

San Miguel Station
6200 FM 3387
Christine, TX 78012

Other features of the plant include the following:

- Boiler: Unit 1, 450 MW – the boiler was manufactured by B&W and is front and rear wall-fired and equipped with separate overfire air and low-NO_x burners for reduced NO_x emissions.

- Seven coal feeders.

- Seven MPS-89 mills for coal grinding.

- Fuel: 4800–5500-Btu (as-received) Texas lignite. Coal is mined approximately 3 miles from the plant in the San Miguel Mine.

- Low-NO_x burners with separate overfire air.

- ESPs for particulate control.

- WFGD for SO_x emissions.

A schematic of Unit 1, with sampling and injection locations, is shown in Figure 3.

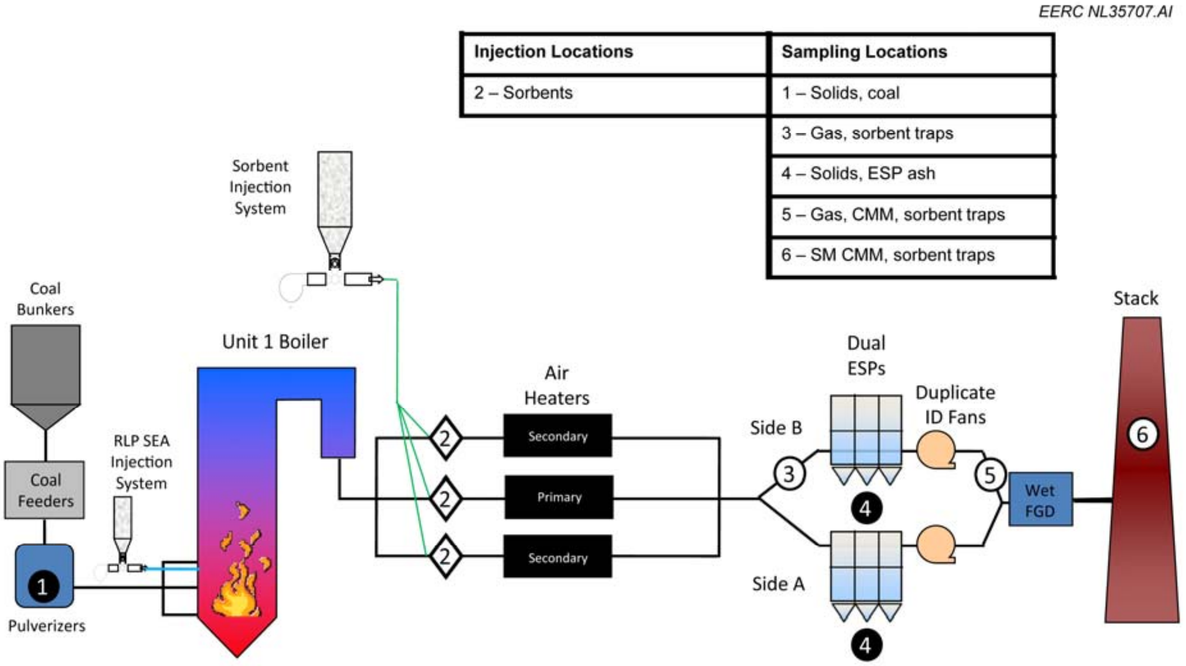


Figure 3. San Miguel Unit 1 schematic showing injection and sampling locations.

TEST PLAN

To address the project objectives, the EERC assisted SMEC in planning for and proceeding with testing of sorbents and SEAs for mercury removal to target a ≥90% mercury removal rate. Tests were performed at San Miguel Unit 1 (450 MW gross) and included injection into the inlet of the AH (temperature of 708°F), Location 2, as shown in Figure 3. Sorbents were injected into the primary and both of the secondary AHs. The RLP Energy SEA was injected directly into the furnace and treated the entire unit. The B&W scrubber additive was injected into the scrubber at two of the four scrubber absorber modules. Flue gas sampling was limited to Side B to minimize duplication of sampling effort and associated costs, as shown in Figure 3.

A test matrix was developed as part of the SSTP to evaluate potential sorbent-based technologies provided by Norit Americas as well as sorbent and SEA technologies provided by RLP Energy that could potentially meet a ≥90% mercury removal target. The B&W scrubber additive was also incorporated into the test matrix. Over the 3-week period, the EERC tested injection of both treated and untreated ACs provided by Norit Americas, select sorbent–SEA combinations provided by RLP Energy, and a scrubber additive provided by B&W. The injection locations for each technology are presented in Figure 3. Baseline, parametric, and extended tests were completed with the various technologies according to the schedule shown in Table 2.

ACs from Norit Americas

Two types of ACs from Norit Americas were used in this test regime. The first was the standard DARCO Hg, which is a “plain,” nontreated carbon that was used for baseline

Table 2. Average Coal Values for the Test Coal

	As-Received Basis	
Parameter	Average[a]	Std. Dev.
Hg, ppm	0.193	0.024
Halogens, ppm	563	58
Br, ppm	3.52	0.67
Proximate Analysis, wt%		
Moisture	31.1	0.92
Volatile Matter	24.90	0.49
Fixed Carbon	21.64	1.01
Ash	22.35	1.74
Ultimate Analysis, wt%		
Hydrogen	2.87	0.10
Carbon	30.77	1.11
Nitrogen	0.46	0.02
Sulfur	2.67	0.10
Oxygen	9.77	0.57
Heating Value, Btu/lb	5281	192

[a] Average values are based on 18 samples.

comparisons. The second was a brominated treated carbon, referred to as DARCO Hg-LH, which is typically used with low-halogen coals to enhance mercury capture. All ACs provided by Norit are readily available in large quantities adequate to supply SMEC.

Sorbents and SEAs from RLP Energy

Two types of sorbents from RLP Energy were used in this test regime. The first was a carbon-based material referred to as SB11. The second sorbent is a non-carbon-based sorbent referred to as SB26. The SEA utilized for the test was SF11. All materials provided by RLP Energy are readily available in large quantities adequate to supply SMEC.

Flue Gas Sampling

To determine baseline emissions and technology effectiveness, mercury percent removals were calculated using inlet flue gas mercury concentrations as well as mercury-in-coal concentrations compared to stack and scrubber inlet mercury concentrations. The EERC installed and operated a CMM at the scrubber inlet and utilized the SMEC stack CMM throughout the duration of the testing to measure gaseous mercury concentrations in the flue gas. The CMMs were primarily used to monitor total gas-phase mercury, but adequate elemental mercury data were also collected.

The EERC-installed CMM at the scrubber inlet was a Tekran with a wet conversion system. The analyzer utilizes a cold-vapor atomic fluorescence spectroscopy (CVAFS) detection method. The wet conversion system precedes the analyzer to continuously reduce Hg^{2+} to elemental mercury Hg^0, resulting in a sample stream of total mercury. For elemental mercury measurements, the oxidized mercury is not reduced, and only the flue gas elemental mercury is measured. Data are obtained every 2.5 minutes on the Tekran CMM. This system was calibrated daily by an EERC CMM operator using Hg^0 as the primary standard to ensure proper quality assurance/quality control (QA/QC).

The SMEC stack CMM was manufactured by Thermo Scientific and is based on CVAFS to detect the gaseous mercury. This system utilizes a dry conversion system and is capable of collecting data every 30 seconds to 5 minutes. This analyzer is able to provide both total and elemental mercury numbers at the same time. During the test period, the analyzer was set to collect a data point every minute. The system was calibrated daily with a Hg^{2+} source that was passed through the conversion catalyst via a calibration sequence setup in the instrument software program. The stack CMM was unable to provide reliable data as a result of unknown problems further discussed in the section on “Baseline Conditions.”

Coal and ash sampling was used to determine inlet and outlet mercury flows and compare them to flue gas measurements. In addition, OH and ST samples were periodically collected to verify CMM instrumentation. OH samples were also collected to obtain mercury speciation data at the scrubber inlet and stack. The ST and OH samples were analyzed in the on-site laboratory to provide for rapid turnaround and feedback regarding the effectiveness of the sorbent methodology used. ST and OH sampling have been shown to be appropriate and accurate for short-term mercury measurement in pulverized coal-fired combustion units and was successfully carried out for this project. The ST samples were collected with dual two-stage traps and were recovered and analyzed for mercury in the EERC mobile lab set up on-site. The OH sampling was performed according to ASTM International (ASTM) Method D6784-02. Appropriate spikes and blanks were also analyzed for QA/QC purposes.

The EERC’s mobile laboratory trailer was taken on-site to support both injection and sampling activities. The on-site analysis allowed a quick turnaround on analyses of OH and ST samples and included blanks and spikes to ensure proper QA/QC and confidence in the results obtained. Analysis of the ST samples was performed in the field with an OhioLumex mercury analyzer. This instrument is designed for on-site “direct” testing of STs. The method is a thermal decomposition procedure validated by EPA. The analyzer uses cold-vapor atomic absorption spectroscopy (CVAAS) to measure the mercury concentration. Analysis of the OH samples was performed in the field with a Leeman Labs Hydra AA spectrometer in accordance with ASTM Method D6784-02 (OH method). The system features dual-beam optics, a 30-cm absorption cell, a built-in autosampler, an integrated gas–liquid separator, and overrange protection. The Hydra AA has a lower detection limit of 1 part per trillion (ppt).

The QA/QC program for analyzing the STs using the OhioLumex consisted of an initial periodic analysis of blanks, calibration, and check standards as a continuing check on performance and, finally, maintaining performance records that define the quality of the data that are generated. The EERC chemist who performed the analysis is well trained and understands the procedures for using the OhioLumex for doing this analysis both in the laboratory and in the field. The following outlines the calibration standards and QA/QC procedures that were followed:

- Calibration standards were prepared from National Institute of Standards and Technology (NIST)-traceable standards to span the range of sample values; the generated calibration curve was required to have an r^2 value greater than 0.99. If these requirements were not met, then the instrument was recalibrated with remade standards if necessary.

- A QC standard was made from a NIST-traceable standard from a different lot than the calibration standards and analyzed to compare to the calibration curve. This standard was required to be within ±5% of its expected value. If it was not, then either the QC standard was remade and analyzed again, or the instrument calibration was rechecked. It should be noted that, for this project, all QC standards fell within the ±5% specification.

- Analyzer calibrations are usually very stable and may be used for several days; the EERC either made or verified the calibration curve each day. QC checks at the high and low calibration on the curve were done a minimum of twice a day (once after generating and verifying the calibration curve and once near the end of the day).

- A QA check at a concentration close to that being analyzed was made for every ten samples or at least twice a day. If these values were within ±10% of the known standard, the calibration was still valid.

- If a calibration had to be repeated after the samples were analyzed, the data for all samples analyzed since the last valid calibration were recalculated based on the new calibration curve. Because the samples were completely desorbed, it was not possible to run them again; therefore, a recalculation was done using computational processes based on the manufacturer's instructions for the calculation of data. It should be noted that for this project, all check standards fell within the ±10% specification.

- Failure to meet the performance criteria may require any or all of the following: remaking calibration and check standards, recalibration of the analyzer, or recalculation of the data.

- All documentation was recorded in project notebooks and/or on the computer. Data records stored on a computer were maintained and backed up. Following testing, all data sheets and log books were initialed by the person completing the analysis and reviewed for completeness and accuracy. Any changes or corrections that needed to be made were initialed, dated, and noted.

Solids Sampling and Analysis

To evaluate mercury input into the system, numerous coal and ash samples were collected throughout the test period; two coal and ash samples were collected and archived each day: one in the morning and one in the afternoon. Analysis of these samples was performed by the EERC at its laboratories. The coal samples were analyzed for Hg, Br, Cl, As, Se, proximate–ultimate, and higher heating value (HHV) using standard ASTM and/or EPA methods.

Plant Data

Operational data, as shown in Appendix A, were monitored and recorded, including unit load, coal flow, mills in service, flue gas temperatures (stack, AH inlet, AH outlet), and CMM readings (stack gas flow, boiler SO_2, boiler CO, boiler NO_x, and boiler O_2).

TEST EQUIPMENT

Sorbent injection was performed with two Norit portable sorbent injection skids. Two skids were needed because of the long hose length (~400 ft) required to reach the injection location and the high lb/hr feed rates required. All back-end sorbents were stored on-site in 1000-lb- or 2000-lb-capacity bulk bags and transported to the injection skid via forklift. The injection system dispenses sorbents via a screw feeder and eductor into the transport line. Motive air is provided by a roots-type blower to convey the sorbent through the transport lines, splitters, and injection lances.

Calibration of the injection skids was completed on-site via measurement of weight versus time. Calibration took place for each material tested at three different rates to generate a calibration curve. The sorbent feed rates in lb/Macf were calculated based on the lb/hr feed and flue gas flow calculated from coal combustion.

The AH inlet injection location was in the duct upstream of the AH and downstream of the split in the ductwork coming out of the boiler, as shown in Figure 3. The primary AH had four lances and each secondary AH had one lance for a total of six lances. Entrained sorbent from the skids was transported to the injection location with a 3-inch convey hose to a 6-way line splitter to distribute the sorbent to the six ports.

RESULTS AND DISCUSSION

A total of 18 coal samples were analyzed for Hg, Br, Cl, As, Se, proximate–ultimate, and HHV using standard ASTM or EPA methods. Proximate and ultimate analyses were conducted on composite coal samples using ASTM Methods D3172, D5142, and D3176. A Mitsubishi Model TOX-100 total halogen analyzer was used to perform ASTM Method D6721-01 (Standard Test Method for Determination of Chlorine in Coal by Oxidative Hydrolysis Microcoulometry). This method actually measures all halogens in the coal, not just chlorine. Coal bromine concentrations were determined via a coal combustion method followed by off-line inductively coupled plasma (ICP) mass spectrometry detection. As and Se coal concentrations were determined via an acid digestion technique followed by ICP atomic emission spectroscopy detection. Coal mercury content was determined using CVAAS according to EPA Method 245.1 and EPA SW-846 Method 7470.

Averages of the test coal analyses are presented in Table 3. The complete coal data set is presented in Appendix B. The analyses represent the average of all 18 coal samples collected during the test period. The standard deviations for the proximate and ultimate analyses show that

Table 3. Calculated Hg Flue Gas Concentrations Based on Hg Coal Concentrations

Parameter	Average[a]	Std. Dev.
Hg, ppm (in coal, as-received basis)	0.193	0.024
Hg, µg/Nm^3 (calculated from coal)	33.16	3.33
Hg, lb Hg/TBtu (calculated from coal)	25.1	6.85

[a] Average values are based on 18 samples.

some variation was present, but this was expected because of the variability of the coal combusted at San Miguel. The chlorine and bromine coal concentrations remained fairly consistent throughout the coal samples. The mercury concentration varied greatly and will be discussed in the next section.

Mercury in Coal

The coal mercury concentration was determined for all samples submitted for analysis, and the average mercury concentration is presented in Table 2. Estimates of mercury concentration levels on a flue gas basis have been prepared using a combustion calculation method that is based on the proximate analysis, ultimate analysis, and coal Btu value. These values are summarized in Table 3.

Figure 4 plots the mercury concentrations for each of the coal samples analyzed. These grab samples were collected on the third floor of the plant, just before the coal feeders. A ball valve was opened in order to catch part of the coal flow that was entering the feeder. The coal collected was predominantly a dustlike consistency, with periodic larger chunks present. Two samples were collected each day, one in the morning and one in the afternoon. In order to determine the mercury concentration in the coal samples, an acid-leaching procedure was used followed by analysis using CVAAS. The mercury concentrations were highly variable, even within the morning and afternoon samples collected on the same day. This was somewhat expected because of the high mercury variability in the coal and the amount of coal burned each hour. The average mercury concentration for the 18 grab samples was 0.193 ppm, with a standard deviation of 0.053 ppm. The measured concentrations had a range of 0.161 to 0.396 ppm.

Figure 5 is a plot of the calculated flue gas mercury concentrations based on coal mercury concentrations. The combustion calculations use the coal mercury concentration along with the proximate and ultimate analyses to calculate an inlet flue gas mercury concentration. Since this calculation is based on the coal mercury numbers, the flue gas mercury concentration also shows a significant amount of day-to-day variability. The coal mercury concentrations ranged from 25.99 µg/dNm^3 at 3% O_2 to 66.41 µg/dNm^3 at 3% O_2, with an average value of 33.16 µg/dNm^3 at 3% O_2. Because of the limited coal samples and the high degree of variability in the coal mercury concentrations, mercury percent removals were calculated based on inlet flue gas mercury concentrations.

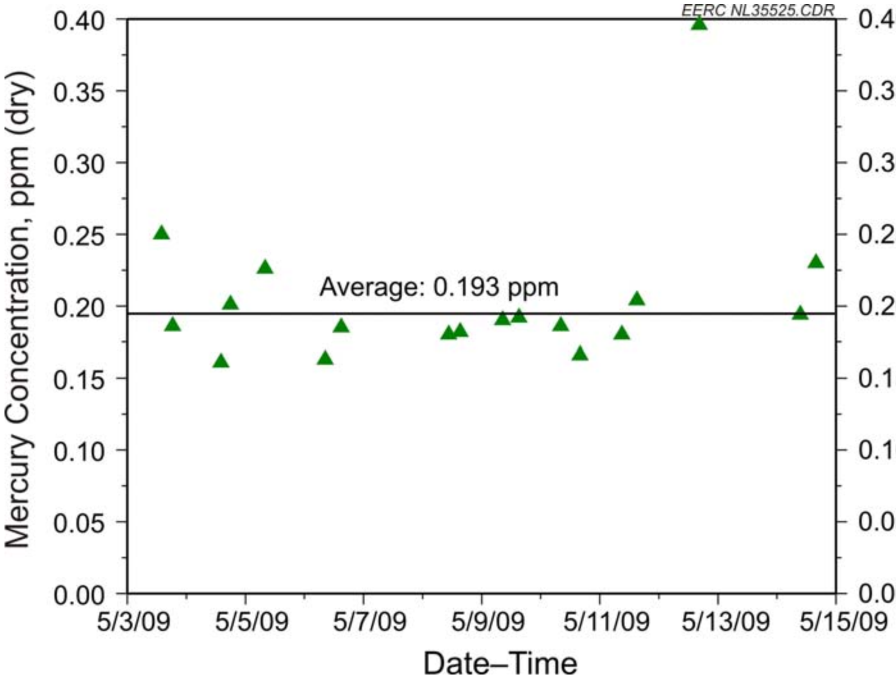


Figure 4. Comparison of day-to-day mercury concentrations in the test coal.

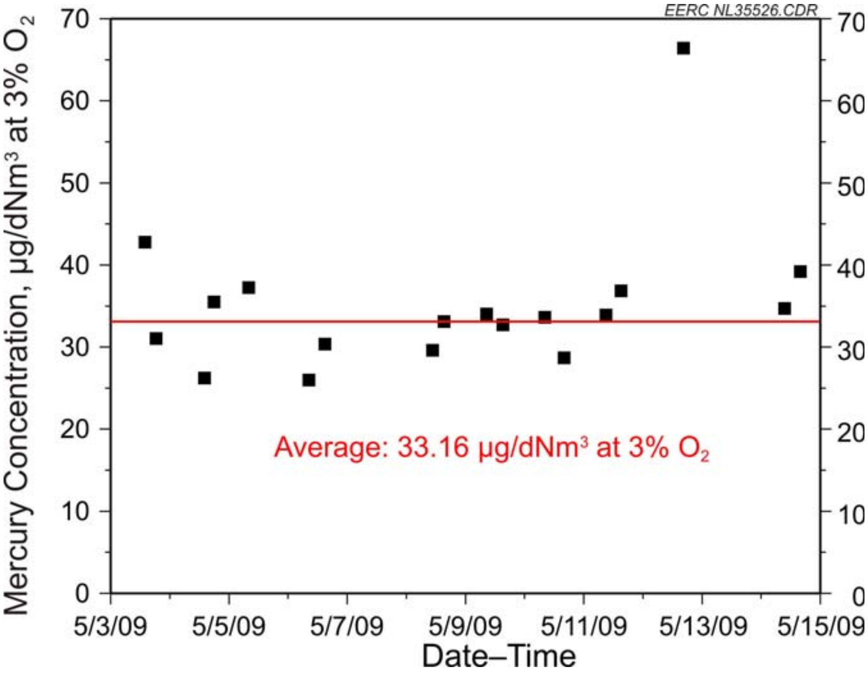


Figure 5. Inlet flue gas mercury concentrations calculated from combustion calculations.

Baseline Conditions

The first 3 days of testing consisted of baseline testing. During baseline testing, the plant conditions and Hg concentrations were measured to determine if there were any periodic changes associated with normal plant operations. Coal and ash samples were taken during baseline testing, and ST and OH sampling were also performed. The CMM was also continuously operated during this period. Appendix C presents the complete CMM, OH, and ST data sets. Appendix D provides sample calculations which show how the CMM, OH, sorbent trap, and lb/Macf calculations were carried out for the data in this report.

During the course of the baseline, parametric, and extended tests, the plant stack CMM was not functioning properly and did not provide any reliable data during the test period. The stack CMM was removed from the stack a few weeks prior to the EERC coming on-site so that stack repairs could be made. Numerous repairs, calibrations, and cleaning procedures were performed with no success. Since the stack CMM was not functioning properly, more STs were collected in order to obtain stack data. OH sampling was also conducted to obtain mercury speciation data.

ST sampling was performed at each sampling location to obtain inlet flue gas mercury concentrations and verify CMM values at the scrubber inlet and stack. The sorbent trap collected at the ESP inlet during baseline conditions yielded an inlet mercury flue gas concentration of 43.44 µg/dNm^3 at 3% O_2. The scrubber inlet and stack STs that were collected at the same time yielded mercury concentrations of 37.74 µg/dNm^3 at 3% O_2 and 25.11 µg/dNm^3 at 3% O_2, respectively. Based on the ESP inlet and scrubber inlet sorbent traps, the removal across the ESP was 13.1%. Scrubber inlet-to-stack ST measurements show that the scrubber is removing an additional 33.5%. The overall ESP inlet-to-stack ST measurements show a baseline removal of 42.2%. The second set of STs collected at the scrubber inlet and stack show similar mercury concentrations of 36.75/dNm^3 at 3% O_2 and 23.67 µg/dNm^3 at 3% O_2, respectively.

In order to obtain baseline speciated mercury data, OH sampling was conducted at the scrubber inlet and stack-sampling locations. Table 4 displays the elemental and total concentrations for the OH samples collected during baseline conditions. The total mercury number is the sum of the elemental, oxidized, and particulate mercury values determined during the OH test. Only the total and elemental numbers are included in Table 4, while the complete

Table 4. Baseline OH Data

Date Time	Location	Hg^0 µg/dNm^3 at 3% O_2	Hg^T µg/dNm^3 at 3% O_2
5/3/2009 14:36	Scrubber Inlet	19.17	30.83
5/4/2009 11:24	Scrubber Inlet	18.95	30.47
5/4/2009 11:19	Stack	21.79	22.43
5/5/2009 9:47	Stack	22.09	22.50

data set is found in Appendix C. The OH measurements show that 62.2% of the mercury present at the scrubber inlet is present in the elemental form. The stack OH measurements show that 97.7% of the mercury is present in the elemental form. This shows that the scrubber removes the majority of the oxidized mercury present in the flue gas.

The baseline OH data show that scrubber reemission is occurring even during baseline conditions. This is apparent when the elemental mercury concentrations are compared at the scrubber inlet and stack. The average scrubber inlet elemental mercury concentration is 19.06 µg/dNm^3 at 3% O_2, while the stack average elemental mercury concentration is 22.47 µg/dNm^3 at 3% O_2. This shows a 2.88 µg/dNm^3 at 3% O_2 increase in elemental mercury across the scrubber. An increase in elemental mercury across a scrubber indicates that scrubber reemission is occurring.

Figure 6 plots the CMM (total and elemental Hg), ST, and OH data collected at the scrubber inlet during the baseline test period. The CMM data show the high degree of variability in the flue gas mercury concentration, with values ranging from 25–42 µg/dNm^3 at 3% O_2. The ST and OH measurements agree well with the CMM data and are generally within 10% of the CMM data. The proximity of the three independent flue gas measurements provides a high degree of confidence in the scrubber inlet mercury measurements and also verifies that the CMM is providing accurate, reliable data.

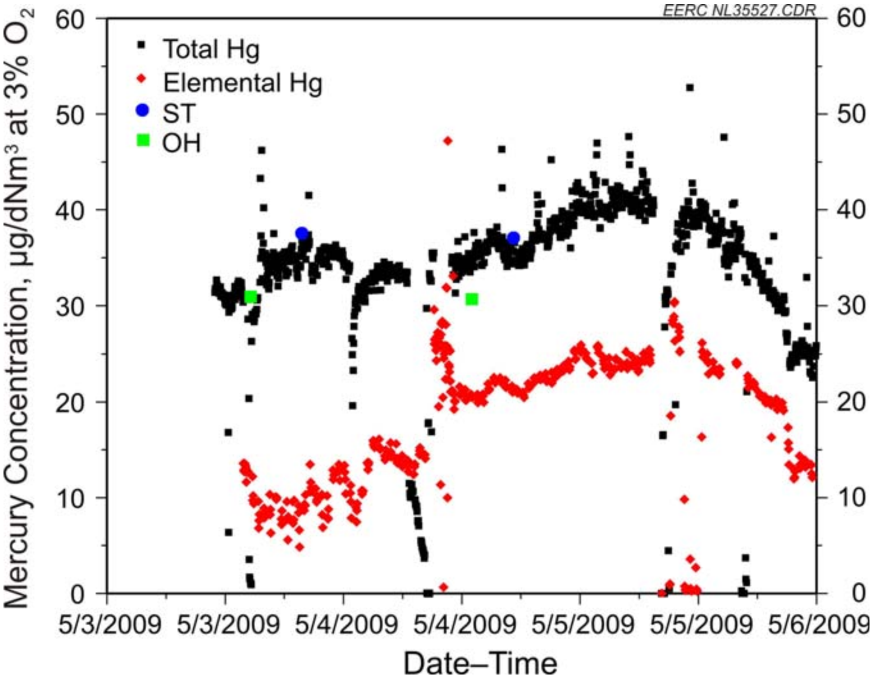


Figure 6. Scrubber inlet baseline mercury measurement data.

Parametric Tests

Following the baseline test period, parametric tests were performed to determine the mercury removal capabilities of sorbents and to evaluate the effectiveness of a scrubber additive solution in reducing scrubber reemission. Each parametric test was performed long enough for the scrubber inlet CMM to reach an apparent steady state, typically for durations of 0.5 to 4 hours. Injections were started at a relatively low rate and then gradually increased to minimize potential memory effects from the higher injection rates. After a parametric test was completed, the next test was not started until the CMM concentrations returned to the values obtained during the baseline test period. During many of the parametric tests, simultaneous ST measurements were made at the scrubber inlet and stack locations to verify the CMM results and obtain data from a different technique than the CMM. Two sets of OH measurements were also collected during the parametric test period in order to obtain mercury speciation data.

DARCO Hg

Initial parametric tests were performed by injection of DARCO Hg into the AH inlet. ST measurements were collected at the highest injection rate tested to verify the CMM at the scrubber inlet and to provide a stack measurement. Figure 7 displays the mercury removal results obtained with DARCO Hg injection at rates ranging from 2 to 4 lb/Macf. The lb/Macf calculations are based on a flow calculation using an ESP inlet temperature of 300°F. At

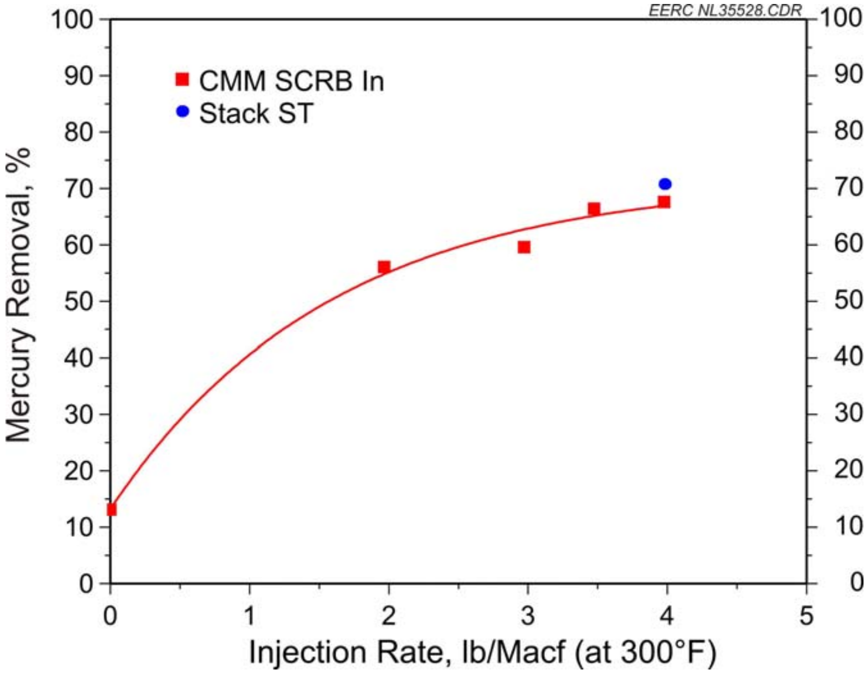


Figure 7. Scrubber inlet mercury removal percentages during DARCO Hg injection.

4 lb/Macf, the mercury removal at the scrubber inlet was 67.6%. The stack ST measurement collected during the same test indicated a mercury removal of 71.5%. The stack and scrubber inlet measurements indicate that most of the removal is occurring across the ESP, which is typical for a plain AC.

DARCO Hg-LH

The next set of parametric tests involved the injection of DARCO Hg-LH into the AH inlet. DARCO Hg-LH is a brominated AC that is designed to increase mercury removals for plants that burn low-halogen coals and coals that have unique properties such as the coal burned at SMEC. Figure 8 displays the mercury removal results obtained during the injection of DARCO Hg-LH at rates ranging from 2 to 3.5 lb/Macf. The mercury removal rates increased slightly as the injection rate was increased, and a maximum removal of 69.9% was obtained at the scrubber inlet at an injection rate of 3.5 lb/Macf. The stack ST that was collected at the 3.5 lb/Macf injection rate yielded a mercury removal of 73.4%. At the 3-lb/Macf injection rate, the scrubber inlet CMM Hg^0 concentrations were 8.61 µg/dNm^3 at 3% O_2 and the Hg^T concentration averaged 13.44 µg/dNm^3 at 3% O_2.

RLP Energy Sorbents and SEAs

Two different sorbents and a SEA provided by RLP Energy were also tested to determine their mercury removal effectiveness at SMEC. The two back-end sorbents tested were SB11 and SB26. SB11 is a carbon-based material, and SB26 is a non-carbon-based material which has

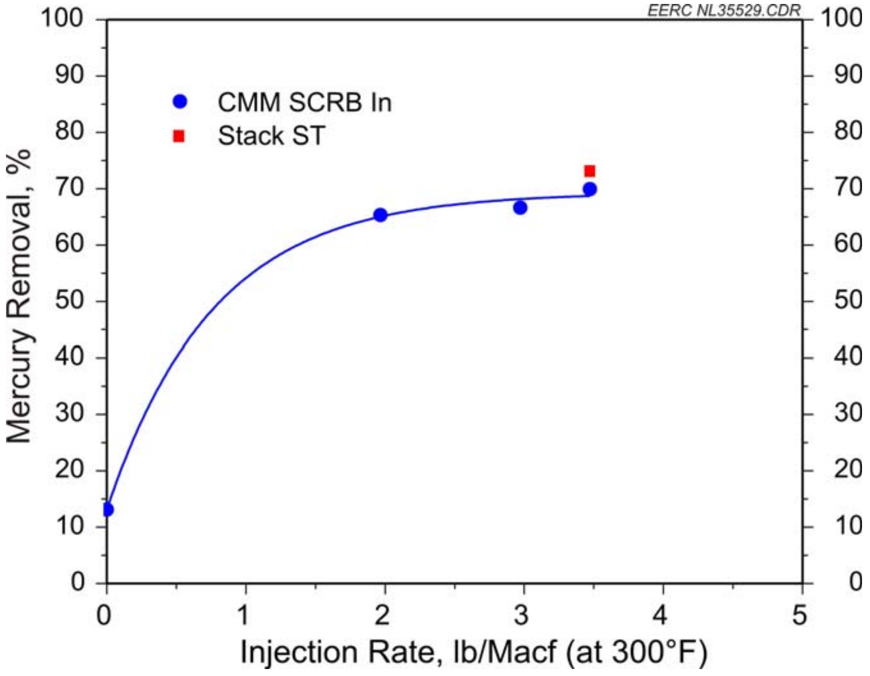


Figure 8. Scrubber inlet mercury removal percentages during DARCO Hg-LH injection.

"concrete-compatible" characteristics. Both sorbents were injected into the AH inlet is the same location as the DARCO and DARCO Hg-LH sorbents. The SEA provided by RLP Energy is a non-carbon-based material called SF11. SF11 was injected into the furnace on the seventh floor.

The first set of parametric tests involved the injection of the SF11 SEA without back-end sorbent injection to evaluate the effectiveness of adding the SEA alone. Figure 9 displays the mercury removal results obtained with the injection of SF11 by itself. Figure 9 shows that there is only a slight increase in mercury removal across the ESP as SF11 rates are increased. At the highest SF11 injection rate of 60 lb/hr, the stack ST measurement shows a mercury removal of 66.3%, which is a significant increase from the 39.4% baseline removal. These data show that SF11 is oxidizing the mercury, but very little of the mercury is interacting with the fly ash in the flue gas and is not removed in the ESP. The oxidized mercury instead travels through the ESP and is subsequently removed in the scrubber.

SF11 was introduced in conjunction with SB11 to evaluate the synergistic effect between the two materials. Figure 10 displays the mercury removal results obtained during the injection of SF11 and SB11. During the parametric tests, both the SF11 and SB11 injection rates were parametrically increased at the same time. As the SF11 and SB11 injection rates were increased, the mercury percent removals exhibited a steady increase. A mercury removal of 67.0% was obtained across the ESP at SF11 and SB11 injection rates of 80 lb/hr and 3.5 lb/Macf, respectively. At these SF11 and SB11 injection rates, a ST was collected at the scrubber inlet location and showed a 65.7% removal across the ESP. This shows that the two independent measurements agree well. The stack ST that was collected at the same time as the scrubber inlet

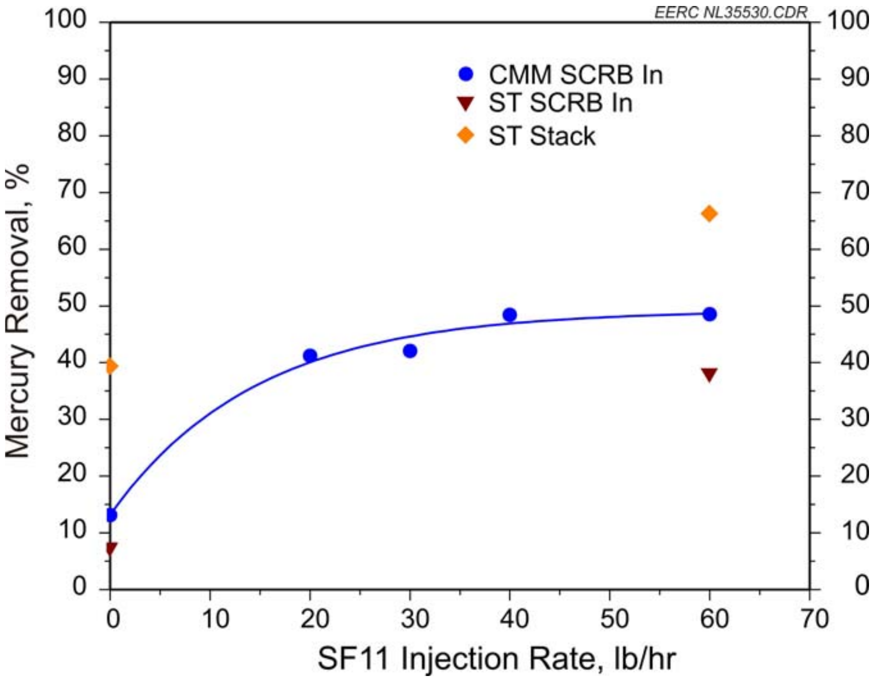


Figure 9. Scrubber inlet mercury removal results during the injection of SF11 into the furnace.

ST yielded a mercury removal of 81.7% at the SF11 and SB11 injection rates of 80 lb/hr and 3.5 lb/Macf, respectively. At the SF11 and SB11 injection rates of 80 lb/hr and 3.5 lb/Macf, the scrubber inlet CMM Hg^0 concentrations dropped to as low as 3.43 µg/dNm^3 at 3% O_2. This shows that the technology combination has the potential to achieve a much higher mercury removal if the scrubber reemission can be reduced or eliminated.

The large circles in Figure 10 show data collected during an extended test with the SF11–SB11 technology combination. For the extended test, the SF11 and SB11 injection rates were 50 lb/hr and 3.5 lb/Macf, respectively. During this 9-hour extended test, the mercury removal across the ESP averaged 57.7%. The stack mercury removal average was obtained via ST measurements and demonstrated an average mercury removal of 72.5%. Figure 11 displays the scrubber inlet CMM data during this time. The Hg^T data remained very stable over the 9-hour period, with an average mercury concentration of 17.04 µg/dNm^3 at 3% O_2. The Hg^0 data showed a little more variance, with an average mercury concentration of 8.74 µg/dNm^3 at 3% O_2, with a range of approximately 7 to 12 µg/dNm^3 at 3% O_2.

A concrete-compatible sorbent, SB26, was also tested in an extended test with SF11 to determine its mercury removal effectiveness at SMEC. The extended test used constant SF11 and SB26 injection rates of 80 lb/hr and 3.5 lb/Macf. The extended test rates were held consistent over a 9-hour period. Figure 12 displays the results of the SF11–SB26 extended test relative to

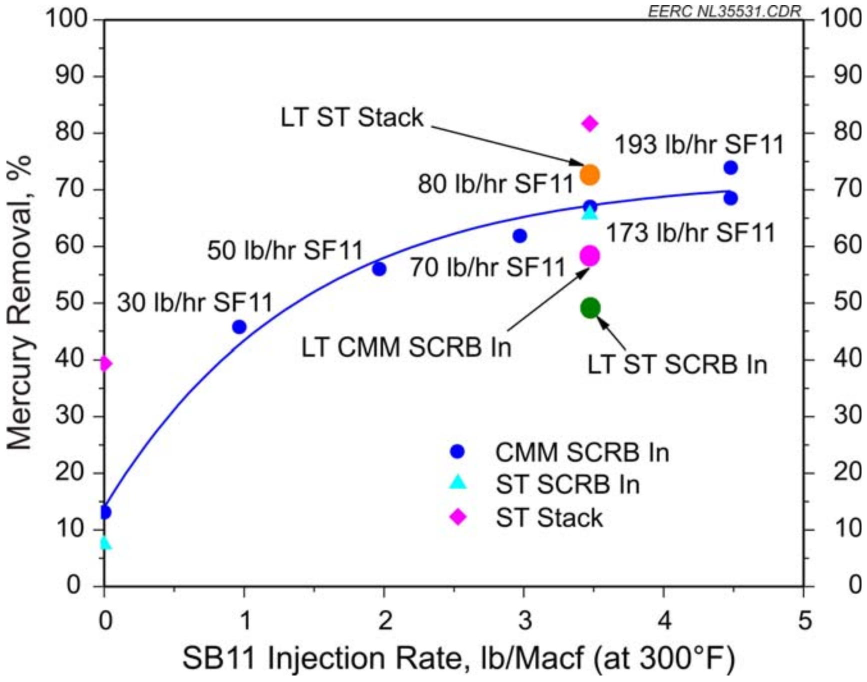


Figure 10. Scrubber inlet mercury removal results during the injection of SF11 into the furnace and the injection of SB11 into the AH inlet. The large circles represent data obtained during the SF10-SB11 extended test.

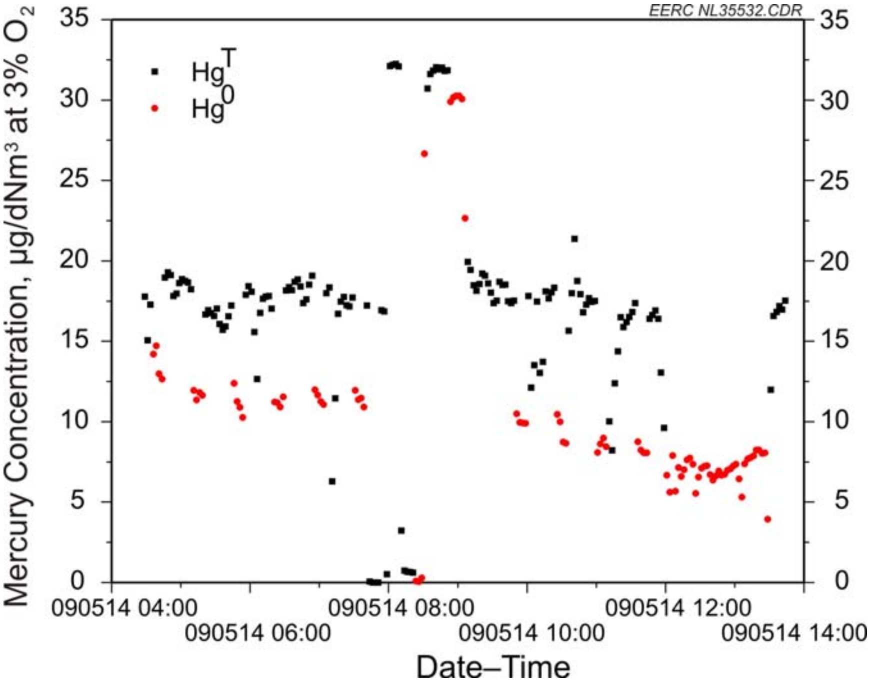


Figure 11. Scrubber inlet CMM data obtained during the SF11–SB11 extended test.

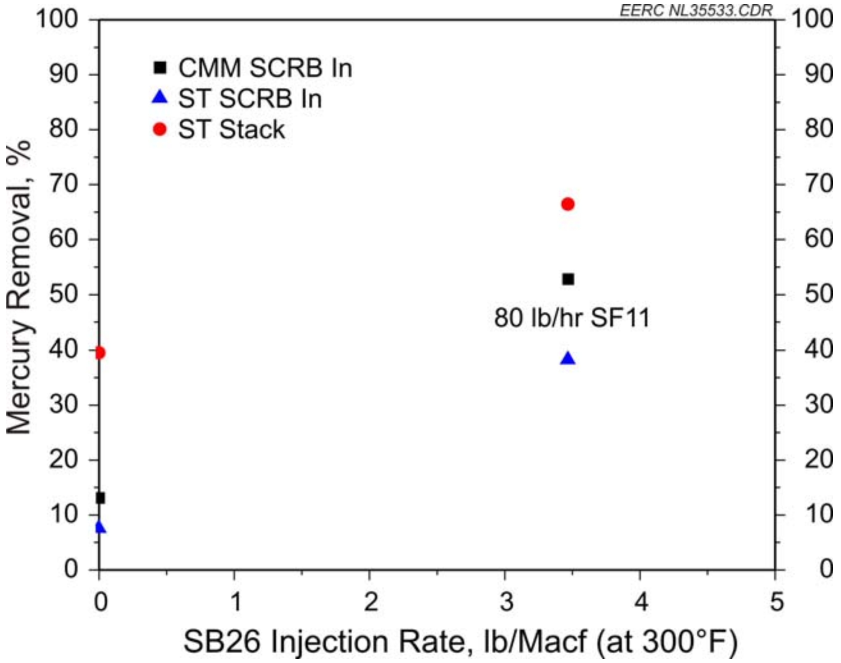


Figure 12. Scrubber inlet CMM data obtained during the SF11–SB26 extended test.

the baseline test conditions. According to the scrubber inlet CMM, a mercury removal of 52.8% was obtained across the ESP. Stack ST measurements yielded a mercury removal of 66.3%. This shows that this technology combination does not offer much improvement over the SF11 additive alone.

B&W Scrubber Additive

In an attempt to reduce or eliminate scrubber reemission at SMEC, a B&W scrubber additive was added to two of the scrubber absorber columns. The scrubber additive rates were parametrically increased from 600 to 1400 lb/hr while DARCO Hg-LH was injected at a constant rate of 3.0 lb/Macf. These parametric tests were typically 3–4 hours in length to allow for the possibility of longer equilibration times of the scrubber additive in the scrubber. Figure 12 shows the mercury removal across the ESP, measured by the scrubber inlet CMM, as the scrubber additive rate is parametrically increased. The constant change shows that the mercury removal across the ESP is constant, which is to be expected since the scrubber is downstream of the ESP. This figure shows that the mercury concentration entering the flue gas was constant for each of the parametric test periods.

Table 5 focuses on the impacts of mercury removal across the scrubber during the scrubber additive parametric tests. Scrubber inlet CMM data, stack ST data, scrubber inlet OH data, and stack OH data were all used to determine if reemission was still occurring and if the scrubber additive had any impact on scrubber reemission. The scrubber inlet CMM Hg^T data are the same data as presented in Figure 13 and show that the removal across the ESP was consistent during the WFGD additive parametric tests. The scrubber inlet CMM Hg^0 column shows that the Hg^0 concentration was also consistent during the parametric testing. The stack ST Hg^T data and the stack OH data agree very well at the 1400-lb/hr scrubber additive injection rate. The stack STs collected at each injection rate show that the mercury removal remained consistent throughout all of the scrubber additive rates tested. When the scrubber inlet Hg^0 data (CMM and OH) are compared to the stack Hg^T data (ST and OH), it is apparent that reemission is still occurring at each scrubber additive injection rate because the scrubber inlet Hg^0 data are 2–4 μg/dNm^3 at 3% O_2 lower than the stack Hg^T data. This amount of reemission is consistent with the parametric

Table 5. Effects of Scrubber Additive on Mercury Removal Across the Scrubber

WFGD Additive Injection Rate, lb/hr	SCRB In CMM Hg^T, μg/dNm^3 at 3% O_2	SCRB In CMM Hg^0, μg/dNm^3 at 3% O_2	Stack ST Hg^T, μg/dNm^3 at 3% O_2	SCRB In OH Hg^T, μg/dNm^3 at 3% O_2	SCRB In OH Hg^0, μg/dNm^3 at 3% O_2	Stack OH Hg^T, μg/dNm^3 at 3% O_2
600	22.29	11.94	14.48	–		–
1000	22.67	12.79	14.03	–		–
1400	22.14	13.54	14.79	18.79	10.86	14.86

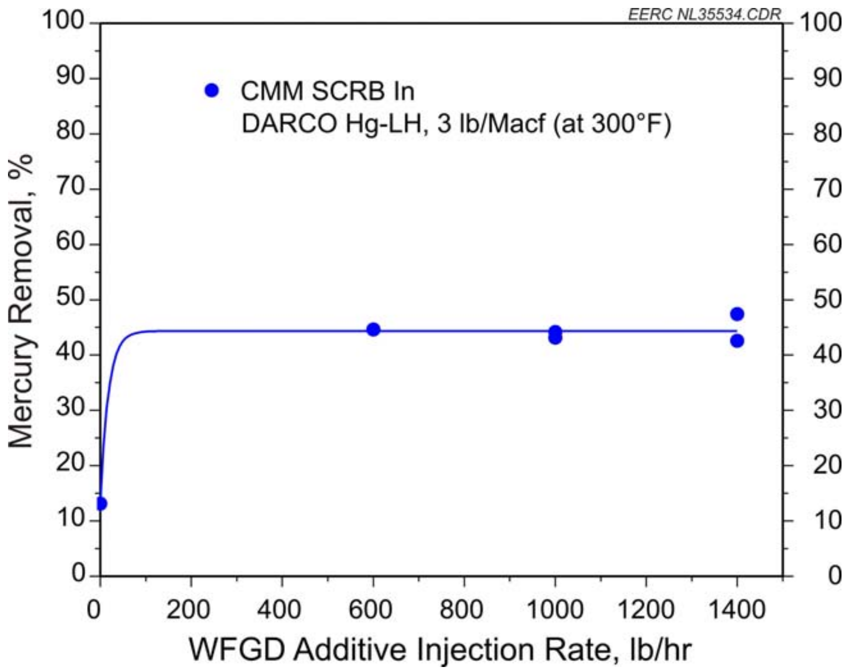


Figure 13. CMM mercury removal results across the ESP during the injection of the scrubber additive.

tests where the scrubber additive was not being tested and indicates that the scrubber additive demonstrated little to no impact on mercury reemission.

CONCLUSIONS

Scrubber reemission remains a critical problem for the SMEC power plant and prevents the plant from obtaining a mercury capture of ≥90%. The B&W scrubber additive tested demonstrated little to no effect on scrubber emission compared to the data obtained in the absence of the scrubber additive.

The SF11–SB11 technology provided by RLP Energy demonstrated an 81.7% mercury removal across the plant at SF11 and SB11 injection rates of 80 lb/hr and 3.5 lb/Macf. This technology achieved results slightly better than other materials tested at SMEC and offers the potential to achieve ≥90% mercury capture if the scrubber reemission can be mitigated.

REFERENCES

1. Olson, E.S.; Laumb, J.D.; Benson, S.A.; Dunham, G.E.; Sharma, R.K.; Mibeck, B.A.; Miller, S.J.; Holmes, M.J.; Pavlish, J.H. An Improved Model for Flue Gas–Mercury Interactions on Activated Carbons. Presented at the DOE–EPRI–EPA–A&WMA Power Plant Air Pollutant Control “Mega” Symposium, Washington, DC, May 19–22, 2003.

APPENDIX A

PLANT OPERATING DATA

PLANT OPERATING DATA

Figure A-1 shows the generated megawatts (MW) for the duration of on-site activities. Figure A-2 shows the coal flow during the testing period. The coal flow varied based on fuel properties and showed noticeable variation during the test period. Figure A-3 shows the primary air and secondary air heater differential pressures. The pressures remained constant during the testing period. Figure A-4 plots the primary and secondary air heater temperatures. The inlet temperatures show a rise and fall in temperatures throughout the testing period. The maximum temperature of each day corresponds to the increase in ambient air temperature throughout the day. Figure A-5 is a stack plot which displays the stack gas flow, boiler SO_2, boiler CO_2, boiler CO, boiler NO_x, and boiler O_2 values during the testing period.

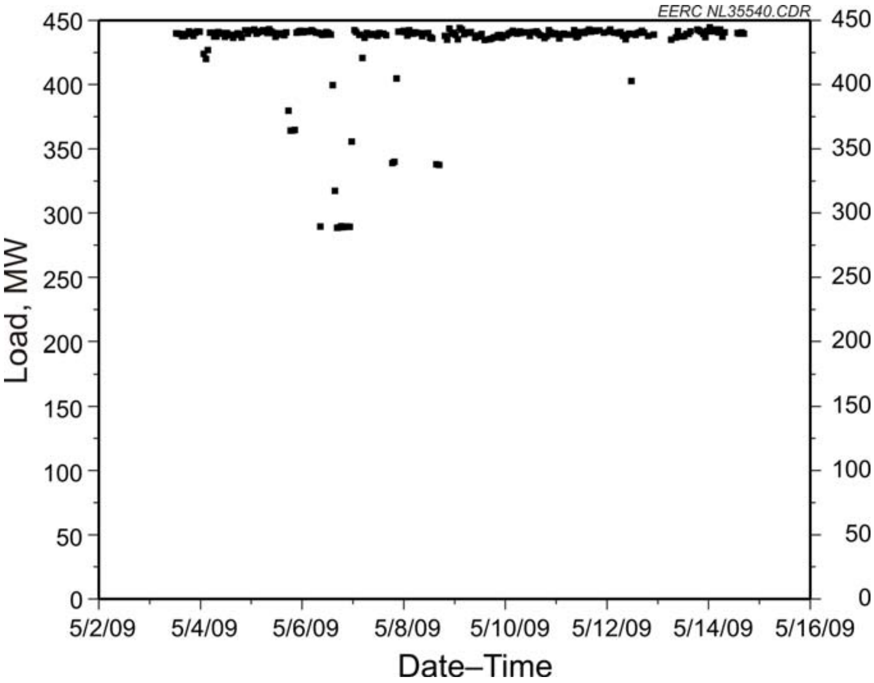


Figure A-1. Generated megawatts for Unit 1.

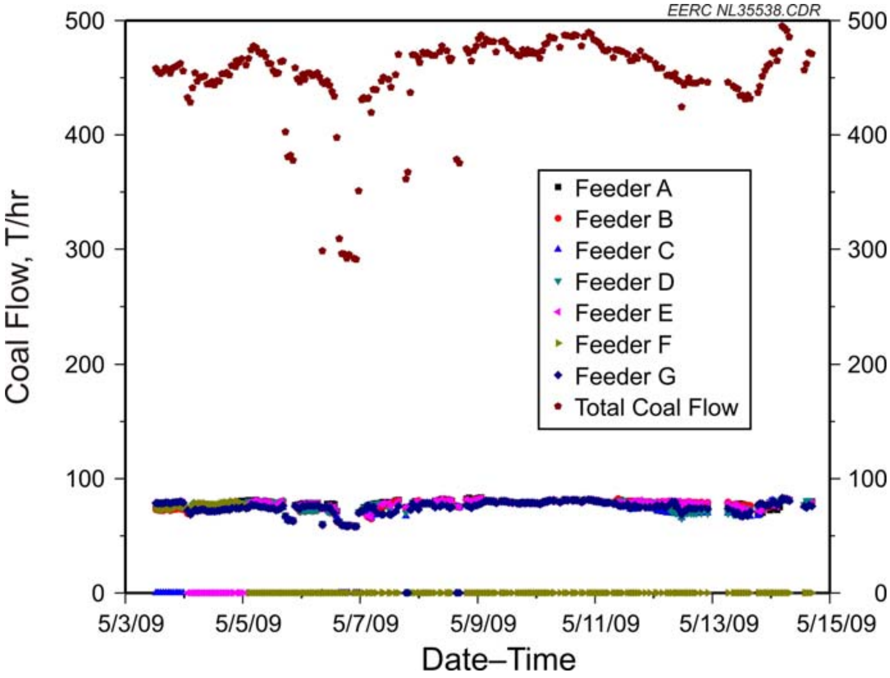


Figure A-2. Total and individual coal feeder flows.

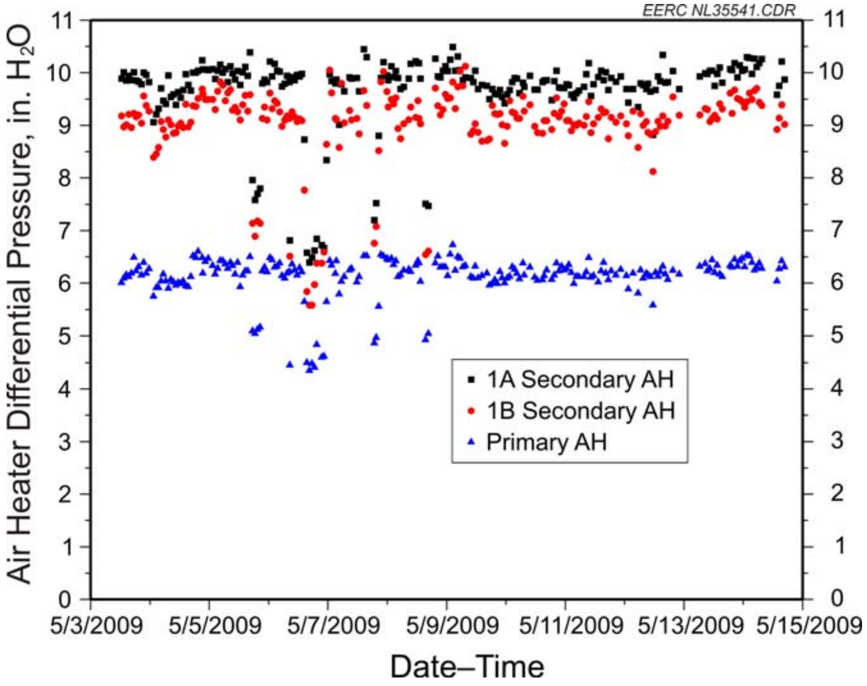


Figure A-3. Primary and secondary air heater differential pressures.

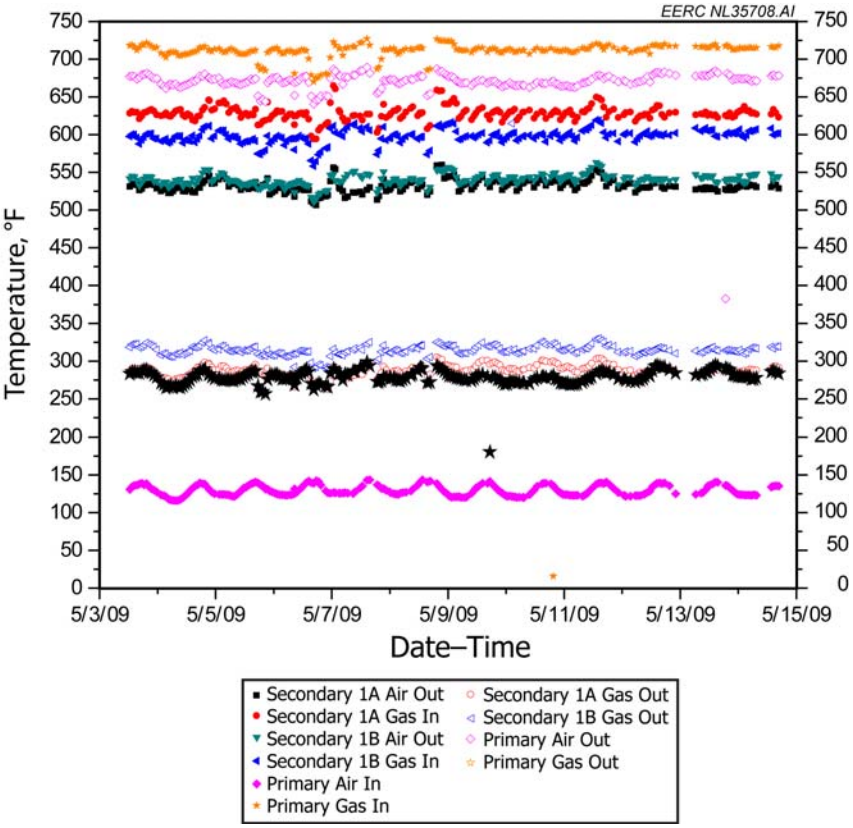


Figure A-4. Primary and secondary air heater temperatures.

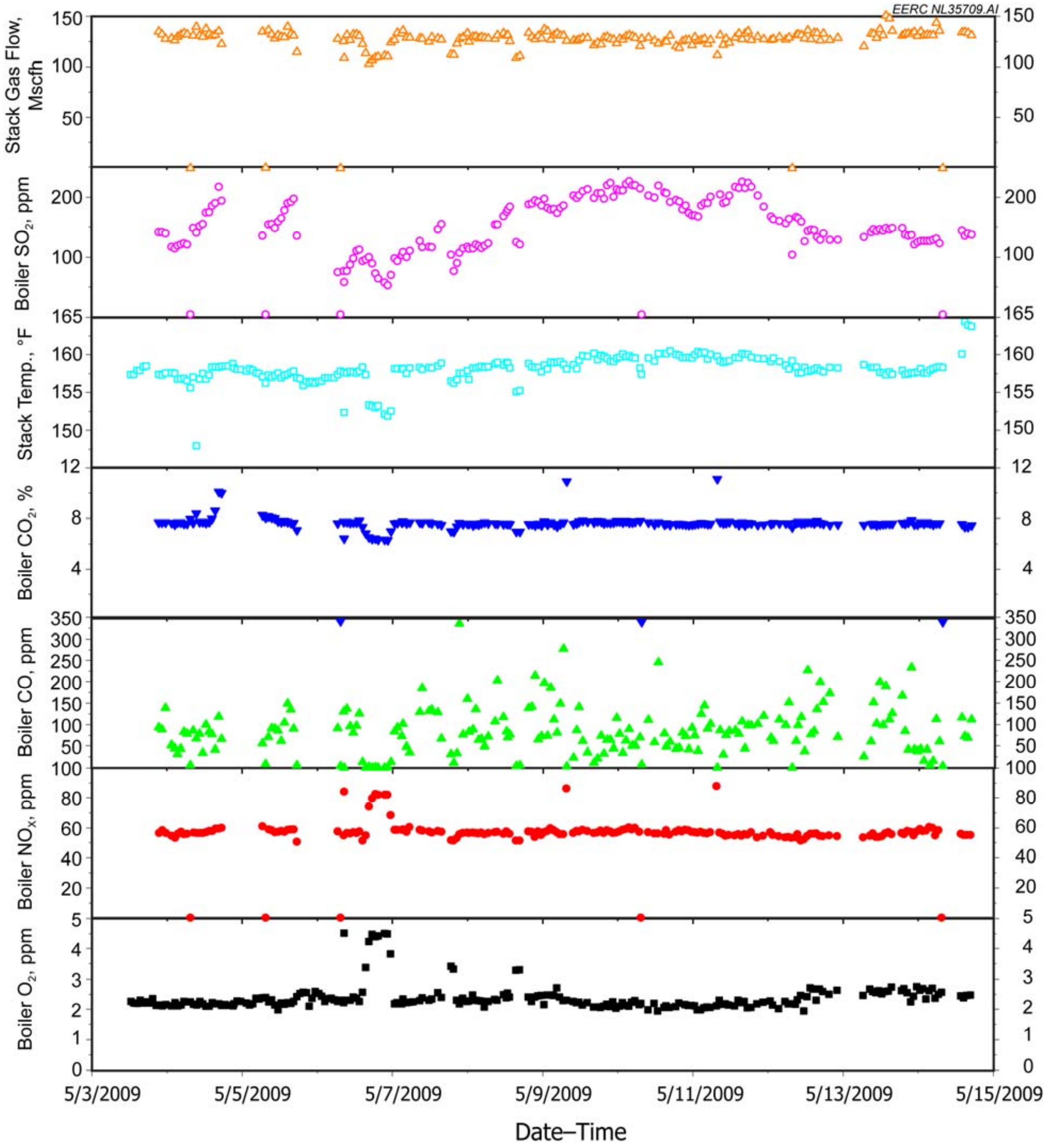


Figure A-5. Additional plant data logged during full-scale baseline and parametric testing.

APPENDIX B

SAMPLE CALCULATIONS

SAMPLE CALCULATIONS

Flue Gas Hg Concentration from Sorbent Trap Samples

Hg (µg/dNm^3 at 3% O_2) = mercury concentration in the flue gas corrected to standard conditions

Hg (µg/dNm^3 at 3% O_2) = (F + S1 + S2) ÷ Vcorr × 18/(21 – O_2)

Vcorr (dNL) = Volume sampled corrected to standard conditions

Vcorr (dNL) = Vm × Cm × (Pb – Elev corr/1000) ÷ 29.92 × 528 ÷ (460 + Tm)

Vcorr (dNL) = 15.0 × 1.070 × (29.94 – 71/1000) ÷ 29.92 × 528 ÷ (460 + 111) = 14.816 dNL

Hg (µg/dNm^3 at 3% O_2) = (0.4 + 108 + 0.5) ÷ 14.816 × 18/(21 – 4.1) = 7.83 µg/dNm^3 at 3% O_2

Where:
Vm = Volume of gas sample measured by the dry-gas meter (dL)
Pb = Barometric pressure (in Hg)
Elev corr = Elevation correction for Pb to sampling elevation (ft)
Tm = Meter temperature (°F)
Cm = Meter correction factor (unitless, via calibration)
O_2 = Flue gas O_2 concentration measured (%)
F = Measured mass of Hg in Front Wool + Plug (ng)
S1 = Measured mass of Hg in Section 1 (ng)
S2 = Measured mass of Hg in Section 2 and plug (ng)

Hg Removal

HgOut = Hg (µg/dNm^3 at 3% O_2) mercury concentration at the outlet location

HgIn = Hg (µg/dNm^3 at 3% O_2) coal mercury concentration

% Hg Removal = The percent of mercury removed from the flue gas based on the inlet and outlet mercury concentrations

% Hg Removal = 100 – (HgOut/HgIn × 100)

% Hg Removal = 100 – (2.2/8.1 × 100) = 72.8%

Ontario Hydro Method Sampling

Volume of Gas Sample

Vm(std) = Volume of gas sample measured by the dry-gas meter, corrected to standard conditions, dscf

$$\text{Vm(std) (dscf)} = \frac{K_1 \times Vmc \times Pm}{Tm + 460}$$

$$\text{Vm(std)} = \frac{17.64 \times 45.472 \times 1 \times 29.665}{104 + 460} = 42.190 \quad \text{dscf}$$

Where:

K_1 = 17.64 R/in. Hg

Vmc = Vm × Cm = Volume of gas sample as measured by dry-gas meter, corrected for meter calibration (Cm = meter calibration coefficient) (dcf)

Pm = Meter pressure (in. Hg)

Tm = Meter temperature (°F)

Volume of Water Vapor

Vw(std) = Volume of water vapor in the gas sample, corrected to standard conditions, scf

Vw(std) (scf) = $K_2 \times H_2O(g)$

Vw(std) = 0.04715 × 137.5 = 6.483 scf

Where:

K_2 = 0.04715 ft^3/g

$H_2O(g)$ = Mass of liquid collected in impingers and silica gel (g)

Water Vapor in the Gas Stream

Bws = Water vapor in the gas stream, proportion by volume

$$\text{Bws} = \frac{\text{Vw(std)}}{\text{Vm(std)} + \text{Vw(std)}}$$

$$\text{Bws} = \frac{6.483}{42.190 + 6.483} = 0.1332$$

Dry Molecular Weight

Md = Dry molecular weight of stack gas, lb/lb-mole

Md (lb/lb-mol) = $0.440 \times (\%CO_2) + 0.320 \times (\%O_2) + 0.280 \times (\%N_2 + \%CO)$

Md = $0.440 \times 15.9 + 0.320 \times 3.1 + 0.280 \times 81.0 = 30.7$ lb/lb-mol

Where:

%(CO_2, O_2, N_2, CO) = Percent (CO_2, O_2, N_2, CO) by volume, dry basis

Molecular Weight

Ms = Molecular weight of stack gas, wet basis, lb/lb-mol

Ms (lb/lb-mol) = $Md \times (1 - Bws) + 18.0 \times Bws$

Ms = $30.7 \times (1 - 0.1332) + 18.0 \times 0.1332 = 29.0$ lb/lb-mol

Average Stack Gas Velocity

Vs = Average stack gas velocity, ft/sec

Vs (ft/sec) = $K_3 \times Cp \times (\Delta p)^{1/2}(avg) \times \left[\frac{Ts + 460}{Ps \times Ms}\right]^{1/2}$

Vs = $85.49 \times 0.84 \times 0.4472 \times \left[\frac{685 + 460}{30.49 \times 29.0}\right]^{1/2} = 36.6\,\text{ft/sec}$

Where:

K_3 = $85.49\,\text{ft/sec} \times \left[\frac{\frac{\text{lb}}{\text{lb-mole}} \times \text{in. Hg}}{R \times \text{in. } H_2O}\right]^{1/2}$

Cp = Pitot tube coefficient, dimensionless

Δp = Velocity head of stack gas (in. Hg)

$(\Delta p)^{1/2}(avg)$ = Average of the square root of Δp values

Ts = Stack gas temperature (°F)

Ps = Stack pressure (in. Hg)

Isokinetic Sampling Rate

I = Percent of isokinetic sampling, %

I (%) = $\frac{K_4 \times (Ts + 460) \times Vm(std) \times 144}{Ps \times Vs \times An \times \theta \times (1 - Bws)}$

I = $$\frac{0.09450 \times (685 + 460) \times 42.190 \times 144}{30.49 \times 36.6 \times 0.0707 \times 90 \times (1 - 0.1332)} = 107\%$$

Where:

K_4 = $$\frac{0.09450\% (\text{in. Hg})(\text{min})}{R \times \text{sec}}$$

An = Cross-sectional area of nozzle (in.^{2})
θ = Total sampling time (min)

Volume of Gas Sample Corrected to 3% O_2

Vm*(std) = Volume of gas sample measured by the dry-gas meter (Vm[std]), * corrected to 3% oxygen, Nm^3

Vm*(std) = $$K_5 \times Vm(std) \times \frac{21 - \%O_2}{18}$$

Vm*(std) = $$0.02832 \times 42.190 \times \frac{21 - 3.1}{18} = 1.188\ \text{Nm}^3$$

Where:

K_5 = 0.02832 m^3/ft^3

Mercury

Hg (µg/Nm^3) = $$\frac{\mu g}{Vm*(std)}$$

Hg = $$\frac{6.99}{1.188} = 5.88\ \mu g/Nm^3$$

Particulate Hg = Sum of mercury from filter and nozzle rinse
Oxidized Hg = Sum of mercury from KCl impingers
Elemental Hg = Sum of mercury from H_2O_2 and $KMnO_4$ impingers

APPENDIX C

COAL DATA

COAL DATA

Coal samples were subjected to analysis for proximate, ultimate, Btu, Hg, As, Se, total halogens, and Br. Tables C-1–C-3 contain the complete results of these analyses. Samples are reported on an as-received basis.

Table C-1. Coal Data May 3–6

Sample Date:		5/3/2009	5/3/2009	5/4/2009	5/4/2009	5/5/2009	5/6/2009
Sample Time:		13:58	18:30	14:08	18:00	8:00	8:30
Hg	ppm (dry)	0.250	0.186	0.161	0.201	0.226	0.163
Total Halogens	ppm (dry)	492	501	539	493	491	519
Br	ppm (dry)	2.40	2.82	2.98	3.04	3.10	5.35
Se	ppm (dry)	4.23	3.93	3.91	4.07	4.11	3.99
As	ppm (dry)	4.36	3.78	3.51	3.41	4.45	3.86
Proximate							
Moisture	%	31.60	31.80	32.00	30.90	32.10	31.80
Volatile Matter	%	24.63	25.30	24.97	24.66	25.43	25.58
Fixed Carbon	%	22.91	21.09	23.11	22.04	21.88	22.40
Ash	%	20.86	21.80	19.93	22.39	20.59	20.23
Total	%	100.00	100.00	100.00	100.00	100.00	100.00
Ultimate							
Hydrogen	%	2.78	2.88	2.94	2.83	2.81	2.96
Carbon	%	31.09	31.22	32.08	30.26	31.77	32.74
Nitrogen	%	0.51	0.47	0.46	0.43	0.50	0.48
Sulfur	%	2.73	2.76	2.82	2.67	2.79	2.74
Oxygen	%	10.43	9.08	9.77	10.51	9.43	9.04
Ash	%	20.86	21.80	19.93	22.39	20.59	20.23
Moisture	%	31.60	31.80	32.00	30.90	32.10	31.80
Total	%	100.00	100.00	100.00	100.00	100.00	100.00
Heating Value	Btu/lb	5336	5349	5496	5211	5462	5643

Table C-2. Coal Data May 6–10

Sample Date:		5/6/2009	5/8/2009	5/8/2009	5/9/2009	5/9/2009	5/10/2009
Sample Time:		14:55	10:37	15:15	8:30	15:11	8:15
Hg	ppm (dry)	0.185	0.180	0.182	0.190	0.192	0.186
Total Halogens	ppm (dry)	514	622	631	663	625	600
Br	ppm (dry)	2.92	4.03	4.34	3.48	3.82	3.42
Se	ppm (dry)	3.70	3.57	4.19	3.78	3.67	3.61
As	ppm (dry)	4.36	3.66	4.64	4.45	4.13	4.47
Proximate							
Moisture	%	31.70	31.70	30.60	30.80	31.10	30.20
Volatile Matter	%	25.19	24.89	24.34	24.76	24.87	24.91
Fixed Carbon	%	22.28	23.14	20.64	20.12	22.08	19.92
Ash	%	20.83	20.27	24.42	24.31	21.96	24.98
Total	%	99.99	100.01	100.00	99.98	100.00	100.01
Ultimate							
Hydrogen	%	2.94	2.86	2.68	2.78	2.88	2.84
Carbon	%	31.90	32.11	29.55	29.68	31.07	29.52
Nitrogen	%	0.46	0.46	0.44	0.43	0.45	0.42
Sulfur	%	2.71	2.71	2.60	2.57	2.75	2.56
Oxygen	%	9.46	9.85	9.71	9.43	9.79	9.48
Ash	%	20.83	20.27	24.42	24.31	21.96	24.98
Moisture	%	31.70	31.70	30.60	30.80	31.10	30.20
Total	%	100.00	99.97	100.00	100.00	100.00	100.00
Heating Value	Btu/lb	5473	5536	5062	5087	5331	5046

Table C-3. Coal Data May 10–14

Sample Date		5/10/2009	5/11/2009	5/11/2009	5/12/2009	5/14/2009	5/14/2009
Sample Time		15:59	9:00	15:10	16:33	9:30	15:55
Hg	ppm (dry)	0.166	0.180	0.204		0.194	0.230
Total Halogens	ppm (dry)	611	612	610	557	519	526
Br	ppm (dry)	3.51	4.12	3.44	3.26	3.52	3.72
Se	ppm (dry)	3.78					
As	ppm (dry)	4.05	4.02	4.64	4.69	5.17	5.36
Proximate							
Moisture	%	31.00	29.80	30.00	30.90	29.10	32.70
Volatile Matter	%	25.39	24.03	24.82	25.06	25.62	23.85
Fixed Carbon	%	20.61	21.65	20.63	22.55	21.26	21.26
Ash	%	23.00	24.52	24.56	21.50	24.02	22.19
Total	%	100.00	100.00	100.01	100.01	100.00	100.00
Ultimate							
Hydrogen	%	2.88	2.80	2.91	2.95	3.14	2.81
Carbon	%	30.53	28.90	29.57	31.59	30.09	30.27
Nitrogen	%	0.47	0.44	0.43	0.46	0.45	0.47
Sulfur	%	2.65	2.51	2.65	2.78	2.53	2.50
Oxygen	%	9.47	11.03	9.89	9.82	10.68	9.06
Ash	%	23.00	24.52	24.56	21.50	24.02	22.19
Moisture	%	31.00	29.80	30.00	30.90	29.10	32.70
Total	%	100.00	100.00	100.00	100.00	100.00	100.00
Heating Value	Btu/lb	5245	4990	5098	5380	5150	5153

APPENDIX D

CONTINUOUS MERCURY MONITOR, ONTARIO HYDRO, AND SORBENT TRAP DATA

CONTINUOUS MERCURY MONITOR, ONTARIO HYDRO, AND SORBENT TRAP DATA

For this project, continuous mercury monitors (CMMs) were set up at the scrubber inlet (Energy & Environmental Research Center [EERC] CMM) and the stack (San Miguel Electric Cooperative [SMEC] CMM). The stack CMM experienced trouble during the entire test duration. The quality assurance/quality control and operating parameters are described in the body of this report. For completeness, the raw CMM data are shown in Figures D-1 and D-2. The raw sorbent trap data collected at the electrostatic precipitator inlet, scrubber inlet, and stack are presented in Tables D-1–D-7. Tables D-8 and D-9 present the raw Ontario Hydro data collected during the test project.

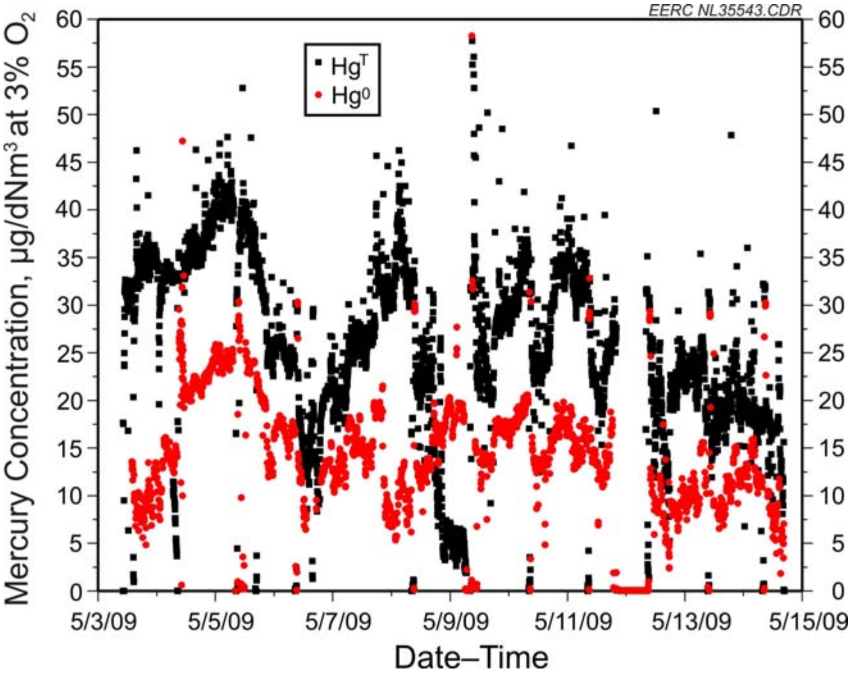


Figure D-1. Scrubber inlet CMM (EERC CMM) data collected during the test project.

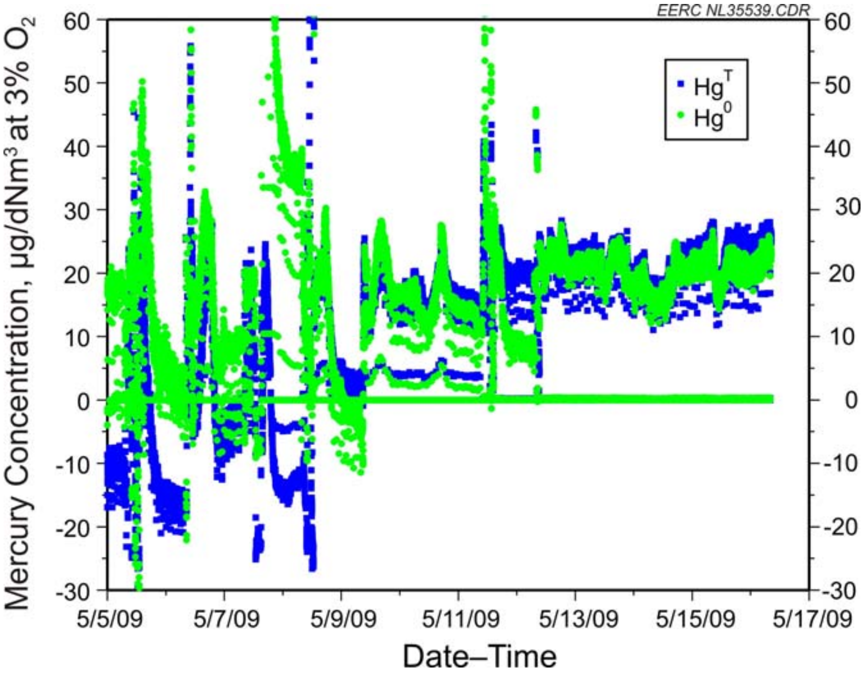


Figure D-2. Stack CMM (SMEC CMM) data collected during the test project.

Table D-1. Sorbent Trap Sample Data

Date		5/3/2009	5/3/2009	5/3/2009	5/4/2009	5/4/2009	5/4/2009
Start Time		19:25	19:01	19:00	16:58	17:01	16:27
Stop Time		19:55	20:01	20:00	17:28	17:46	17:27
Duration	min	30	60	60	30	45	60
Location		ESP In	SCRB In	Stack	ESP In	SCRB In	Stack
Trap ID	No.	45803	45938	46049	46056	46079	45976
Vm	dL	12.4	25.5	31.2	13.1	18.1	33.2
Pb	in. Hg	29.29	29.29	29.29	29.41	29.41	29.41
Elev. Corr.	ft	75	80	295	75	80	295
Tm	°F	101	95.6	95.2	100.5	99.8	96.6
Cm		0.974	1.05	1.037	0.974	1.05	1.037
Moisture	%	0.0	0.0	0.0	0.0	0.0	0.0
O_2	%	8.4	9.9	10.7	8.6	9.8	10.6
Ash	ng	1.6	–	–	0.6	–	–
Plug 1	ng	1.0	2.9	8.6	0.3	6.0	10.0
Sect. 1	ng	335	574	419	190	395	424
Sect. 2 w/Plug	ng	1.5	1.2	0.8	0.5	0.8	0.7
Back Plug	ng	0	0	0	0	0	0
Breakthrough	%	0.4	0.2	0.2	0.3	0.2	0.2
V Corr.	dNL	11.1	24.8	29.8	11.8	17.6	31.8
Hg	$\mu g/dNm^3$	30.41	23.27	14.37	16.19	22.87	13.68
Hg (O_2 corr.)	$\mu g/dNm^3$ at 3% O_2	43.44	37.74	25.11	23.50	36.75	23.67

Table D-2. Sorbent Trap Sample Data

Date		5/6/2009	5/6/2009	5/6/2009	5/8/2009	5/8/2009	5/8/2009
Start Time		12:34	17:57	17:48	11:39	11:33	15:30
Stop Time		13:19	18:18	18:33	12:39	12:33	16:31
Duration	min	45	21	45	60	60	61
Location		Stack	SCRB In	Stack	SCRB In	Stack	SCRB In
Trap ID	No.	45957	46042	46044	45805	45923	46015
Vm	dL	25.2	10.9	25.8	25.5	32.9	24.8
Pb	in. Hg	29.35	29.23	29.23	29.35	29.35	29.23
Elev. Corr.	ft	295	80	295	80	295	80
Tm	°F	99.8	113	101.5	100.8	98.4	111.8
Cm		1.037	1.05	1.037	1.05	1.037	1.05
Moisture	%	0.0	0.0	0.0	0.0	0.0	0.0
O_2	%	10.6	11.7	12.6	10.1	10.8	11.1
Ash	ng	–	–	–	–	–	–
Plug 1	ng	4.5	10.0	2.3	1.1	5.5	1.8
Sect. 1	ng	154	92	117	352	250	321
Sect. 2 w/Plug	ng	0.1	1.7	2.3	1.6	1.6	1
Back Plug	ng	0	0	0	0	0	0
Breakthrough	%	0.1	1.8	2.0	0.5	0.6	0.3
V Corr.	dNL	23.9	10.3	24.3	24.7	31.3	23.4
Hg	$\mu g/dNm^3$	6.63	10.09	5.00	14.38	8.21	13.82
Hg (O_2 corr.)	$\mu g/dNm^3$ at 3% O_2	11.47	19.53	10.71	23.75	14.48	25.13

Table D-3. Sorbent Trap Sample Data

Date		5/8/2009	5/9/2009	5/9/2009	5/9/2009	5/9/2009	5/10/2009
Start Time		15:27	15:17	15:13	16:34	16:30	14:12
Stop Time		16:27	16:16	16:13	17:35	17:30	15:13
Duration	min	60	59	60	61	60	61
Location		Stack	SCRB In	Stack	SCRB In	Stack	SCRB In
Trap ID	No.	45977	45912	46706	45880	46696	46047
Vm	dL	34.8	24.9	33.7	25.1	33.8	25.1
Pb	in. Hg	29.23	29.41	29.41	29.38	29.43	29.50
Elev. Corr.	ft	295	80	295	80	295	80
Tm	°F	104.8	111	102.6	120.8	103.6	96.4
Cm		1.037	1.05	1.037	1.05	1.037	1.05
Moisture	%	0.0	0.0	0.0	0.0	0.0	0.0
O_2	%	11.6	9.6	10.6	9.6	10.6	9.6
Ash	ng	–	–	–	–	–	–
Plug 1	ng	3.8	2.8	11.0	0.4	5.7	0.5
Sect. 1	ng	235	367	261	350	234	452
Sect. 2 w/Plug	ng	0.2	1	0.8	3.8	0.1	1.1
Back Plug	ng	0	0	0	0	0	0
Breakthrough	%	0.1	0.3	0.3	1.1	0.0	0.2
V Corr.	dNL	32.6	23.7	31.9	23.5	32.0	24.6
Hg	$\mu g/dNm^3$	7.33	15.65	8.55	15.10	7.50	18.45
Hg (O_2 corr.)	$\mu g/dNm^3$ at 3% O_2	14.03	24.70	14.79	23.84	12.98	29.12

Table D-4. Sorbent Trap Sample Data

Date		5/10/2009	5/10/2009	5/10/2009	5/11/2009	5/11/2009	5/11/2009
Start Time		14:13	15:33	15:31	10:10	10:07	11:31
Stop Time		15:13	16:34	16:31	11:10	11:07	12:31
Duration	min	60	61	60	60	60	60
Location		Stack	SCRB In	Stack	SCRB In	Stack	SCRB In
Trap ID	No.	46684	45896	45989	46106	46669	45955
Vm	dL	33.5	24.8	34.7	25.8	33.8	25.4
Pb	in. Hg	29.50	29.44	29.44	29.53	29.53	29.53
Elev. Corr.	ft	295	80	295	80	295	80
Tm	°F	99.4	105	105	98.4	91.8	108.2
Cm		1.037	1.05	1.037	1.05	1.037	1.05
Moisture	%	0.0	0.0	0.0	0.0	0.0	0.0
O_2	%	10.6	9.6	10.7	9.7	10.6	9.6
Ash	ng	–	–	–	–	–	–
Plug 1	ng	4.4	0.4	11	1.2	52	3.1
Sect. 1	ng	263	437	347	434	269	375
Sect. 2 w/Plug	ng	1.1	1.1	0.9	0.7	0.7	0.8
Back Plug	ng	0	0	0	0	0	0
Breakthrough	%	0.4	0.3	0.3	0.2	0.3	0.2
V Corr.	dNL	32.0	23.9	32.8	25.2	32.8	24.4
Hg	µg/dNm^3	8.39	18.36	10.96	17.29	9.82	15.53
Hg (O_2 corr.)	µg/dNm^3 at 3% O_2	14.52	28.99	19.15	27.54	16.99	24.53

Table D-5. Sorbent Trap Sample Data

Date		5/11/2009	5/11/2009	5/11/2009	5/12/2009	5/12/2009	5/12/2009
Start Time		11:29	13:50	13:49	12:27	12:26	16:38
Stop Time		12:29	14:49	14:49	13:27	13:26	17:36
Duration	min	60	59	60	60	60	58
Location		Stack	SCRB In	Stack	SCRB In	Stack	SCRB In
Trap ID	No.	46056	45881	46327	46038	45878	45671
Vm	dL	34.0	24.9	34.6	25.4	33.5	25.1
Pb	in. Hg	29.53	29.50	29.50	29.50	29.50	29.38
Elev. Corr.	ft	295	80	295	80	295	80
Tm	°F	101	110.4	102.6	94.4	98.6	103.4
Cm		1.037	1.05	1.037	1.05	1.037	1.05
Moisture	%	0.0	0.0	0.0	0.0	0.0	0.0
O_2	%	10.5	9.7	10.5	9.7	10.7	9.7
Ash	ng	–	–	–	–	–	–
Plug 1	ng	0.8	0.5	4.4	6.8	6	2
Sect. 1	ng	223	378	237	382	242	207
Sect. 2 w/Plug	ng	3.9	0.6	0.4	1.4	0.9	0.9
Back Plug	ng	0	0	0	0	0	0
Breakthrough	%	1.7	0.2	0.2	0.4	0.4	0.4
V Corr.	dNL	32.4	23.8	32.9	25.0	32.1	24.2
Hg	$\mu g/dNm^3$	7.02	15.93	7.36	15.62	7.77	8.68
Hg (O_2 corr.)	$\mu g/dNm^3$ at 3% O_2	12.04	25.38	12.61	24.89	13.57	13.82

Table D-6. Sorbent Trap Sample Data

Date		5/12/2009	5/13/2009	5/13/2009	5/13/2009	5/13/2009	5/14/2009
Start Time		16:42	13:39	13:40	17:18	17:12	9:34
Stop Time		17:42	14:39	14:40	18:18	18:12	10:34
Duration	min	60	60	60	60	60	60
Location		Stack	SCRB In	Stack	SCRB In	Stack	SCRB In
Trap ID	No.	45934	45932	46109	45990	45804	45807
Vm	dL	34.0	25.3	33.8	25.2	34.5	26.0
Pb	in. Hg	29.38	29.38	29.38	29.32	29.32	29.50
Elev. Corr.	ft	295	80	295	80	295	80
Tm	°F	99.4	96.6	99.6	99.8	96.2	87.2
Cm		1.037	1.05	1.037	1.05	1.037	1.05
Moisture	%	0.0	0.0	0.0	0.0	0.0	0.0
O_2	%	10.6	10.0	10.8	10.0	10.8	9.9
Ash	ng	–	–	–	–	–	–
Plug 1	ng	2.8	2.2	7.7	2	7	0.8
Sect. 1	ng	134	372	239	414	275	357
Sect. 2 w/Plug	ng	0.7	1.1	0.5	0.3	0.5	1
Back Plug	ng	0	0	0	0	0	0
Breakthrough	%	0.5	0.3	0.2	0.1	0.2	0.3
V Corr.	dNL	32.4	24.7	32.1	24.4	32.9	25.9
Hg	µg/dNm^3	4.25	15.21	7.69	17.07	8.57	13.85
Hg (O_2 corr.)	µg/dNm^3 at 3% O_2	7.36	24.89	13.57	27.93	15.13	22.46

Table D-7. Sorbent Trap Sample Data

Date		5/14/2009	5/14/2009	5/14/2009
Start Time		9:34	10:51	10:51
Stop Time		10:34	11:52	11:51
Duration	min	60	61	60
Location		Stack	SCRB In	Stack
Trap ID	#	45836	45929	46054
Vm	dL	33.6	25.2	34.2
Pb	in Hg	29.50	29.53	29.53
Elev. Corr.	ft	295	80	295
Tm	°F	87.2	91.8	91.2
Cm		1.037	1.05	1.037
Moisture	%	0.0	0.0	0.0
O_2	%	10.9	9.9	10.9
Ash	ng	–	–	–
Plug 1	ng	6.3	0.9	10
Sect. 1	ng	200	282	192
Sect. 2 w/Plug	ng	0.8	1.3	0.7
Back Plug	ng	0	0	0
Breakthrough	%	0.4	0.5	0.4
V Corr.	dNL	32.8	24.9	33.2
Hg	$\mu g/dNm^3$	6.31	11.40	6.11
Hg (O_2 corr.)	$\mu g/dNm^3$ at 3% O_2	11.25	18.49	10.88

Table D-8. OH Sample Data

Sample ID:		SM-SCRUBin-OH-No. 1	SM-STACK-OH-No. 1	SM-SCRUBin-OH-No. 2	SM-STACK-OH-No. 2
Start Time		5/3/2009 14:36	5/4/2009 11:19	5/4/2009 11:24	5/5/2009 9:47
End Time		5/3/2009 16:36	5/4/2009 13:19	5/4/2009 13:24	5/5/2009 11:47
Duration	hr	2	2	2	2
Hg^P					
Filter	µg/dNm^3	0.00	0.00	0.00	0.01
Hg^{2+}					
Nozzle Rinse	µg/dNm^3	0.00	0.00	0.00	0.05
Probe Rinse	µg/dNm^3	0.38	0.03	0.12	0.01
KCl	µg/dNm^3	6.81	0.33	6.98	0.17
Hg^0					
H_2O_2	µg/dNm^3	0.50	0.31	0.49	0.18
$KMnO_4$	µg/dNm^3	11.32	11.80	11.20	12.34
Total Hg^0	µg/dNm^3	11.82	12.11	11.69	12.52
Total Hg^0, O_2 Corrected	µg/dNm^3 at 3% O_2	19.17	21.79	18.95	22.09
Total Hg^T	µg/dNm^3	19.01	12.46	18.79	12.75
Total Hg^T, O_2 Corrected	µg/dNm^3 at 3% O_2	30.83	22.43	30.47	22.50

Table D-9. OH Sample Data

Sample ID:		SM-SCRUBin-OH-No. 3	SM-STACK-OH-No. 3	SM-SCRUBin-OH-No. 4	SM-STACK-OH-No. 4
Start Time		5/9/2009 10:50	5/10/2009 10:10	5/10/2009 10:06	5/9/2009 10:44
End Time		5/9/2009 12:50	5/10/2009 12:10	5/10/2009 12:06	5/9/2009 12:44
Duration	hr	2	2	2	2
Hg^P					
Filter	µg/dNm^3	0.00	0.02	0.00	0.02
Hg^{2+}					
Nozzle Rinse	µg/dNm^3	0.00	0.00	0.00	0.00
Probe Rinse	µg/dNm^3	0.01	0.00	0.01	0.01
KCl	µg/dNm^3	5.04	0.11	5.01	0.10
Hg^0					
H_2O_2	µg/dNm^3	0.26	0.08	0.31	0.19
$KMnO_4$	µg/dNm^3	2.38	8.38	6.57	1.90
Total Hg^0	µg/dNm^3	2.64	8.46	6.88	2.09
Total Hg^0, O_2 Corrected	µg/dNm^3 at 3% O_2	4.27	14.63	10.86	3.66
Total Hg^T	µg/dNm^3	7.69	8.59	11.90	2.22
Total Hg^T, O_2 Corrected	µg/dNm^3 at 3% O_2	12.47	14.86	18.79	3.89

APPENDIX C

FULL-SCALE TESTING TO EVALUATE MERCURY CONTROL OPTIONS AT THE CENTRALIA GENERATING STATION

EERC
Energy & Environmental Research Center®
Putting Research into Practice

FULL-SCALE TESTING TO EVALUATE MERCURY CONTROL OPTIONS AT THE CENTRALIA GENERATING STATION

University of North Dakota
Grand Forks

FULL-SCALE TESTING TO EVALUATE MERCURY CONTROL OPTIONS AT THE CENTRALIA GENERATING STATION

Final Report

(for the period March 24, 2009, through April 30, 2010)

Prepared for:

John Melink

TransAlta Centralia Generation, LLC
913 Big Hanaford Road
Centralia, WA 98531-1000

Prepared by:

John H. Pavlish
Jeffrey S. Thompson
Nicholas B. Lentz
Lucinda L. Hamre

Energy & Environmental Research Center
University of North Dakota
15 North 23rd Street, Stop 9018
Grand Forks, ND 58202-9018

2010-EERC-04-05

April 2010

DOE DISCLAIMER

ACKNOWLEDGMENT

This report was prepared with support from TransAlta Centralia Generation, LLC, and the U.S. Department of Energy (DOE). However, any opinions, findings, conclusions, or recommendations expressed herein are those of the authors(s) and do not necessarily reflect the views of TransAlta or DOE.

EERC DISCLAIMER

LEGAL NOTICE. This research report was prepared by the Energy & Environmental Research Center (EERC), a department of the University of North Dakota, as an account of work sponsored by TransAlta Centralia Generation, LLC, and the U.S. Department of Energy (DOE). The EERC is a world-class research organization and conducted research testing for TransAlta Centralia Generation, LLC, and DOE in accordance with accepted research and sampling methods. The EERC affirms that all data was subjected to quality assurance/quality control protocols for validity and accuracy.

As a state research entity governed by North Dakota law, neither the EERC nor any of its employees provides any warranty, express or implied, or assumes any legal liability for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement or recommendation by the EERC.

FULL-SCALE TESTING TO EVALUATE MERCURY CONTROL OPTIONS AT THE CENTRALIA GENERATING STATION

ABSTRACT

In North America, testing has been under way at coal-fired electric power plants to find viable and economical mercury control strategies to meet pending regulations. TransAlta Centralia Generation, LLC, along with the U.S. Department of Energy (DOE) contracted with the University of North Dakota's Energy & Environmental Research Center (EERC) to evaluate sorbent-based mercury control technologies at TransAlta's coal-fired Centralia Generating Station. The primary goal was to identify sorbent-based technology options that could be used to meet an overall mercury removal goal of ≥ 80%.

The EERC has successfully pilot- and field-tested several sorbent-based technologies that offer promise and potential to achieve the mercury removal goal of ≥ 80%. Based on these pilot- and field-scale test results, the EERC proposed research tests to evaluate potential sorbent-based technologies provided by RLP Energy and Norit Americas that could potentially meet TransAlta's mercury control objectives. Tests were performed at TransAlta's Centralia Unit 2, 688 MW (net output), which burns a Powder River Basin subbituminous coal supplied via train. From August through October 2009, the EERC evaluated a sorbent enhancement additive (SEA), SF10, and numerous proprietary sorbents provided by RLP Energy, as well as Norit's DARCO® Hg-LH and DARCO Hg-CC (concrete-friendly) mercury sorbents. SF10 was injected into the burner front of the west side of the furnace, and the back-end sorbents were injected into the ducts between the two electrostatic precipitators (ESPs) on both the north and south sides. Later in the test campaign, an alternative SEA proprietary technology was also tested.

Baseline testing was performed for 3 days to evaluate the variability in flue gas mercury concentrations and the inherent mercury removal performance of the unit. The average total mercury concentration obtained from sorbent traps (ST) measurements at the Koppers (first ESP) inlet was 10.48 $\mu g/dNm^3$ at 3% O_2. During baseline testing conditions, average ST data from the Koppers inlet and stack indicated an overall native mercury removal efficiency of approximately 18.5%.

Parametric tests were performed by injecting SF10 into the burner front of the furnace coupled with select sorbents injected between the two ESPs. Several SF10 and sorbent combinations showed promise and were able to achieve ≥ 80% mercury removal, albeit at varying rates of each material. Based on the results of these tests, the best combination—SF10–SB24—was selected for extended testing because it exhibited the greatest mercury removal at the smallest injection rates of materials. Following the parametric tests, four extended tests using SF10–SB24 were conducted for approximately 5 days each, with mercury removals targeted at 60%, 70%, 80%, and >90%.

The mercury removal results for SF10–SB24 ET1 (20 lb/hr, 50 lb/hr), ET2 (25 lb/hr, 100 lb/hr), ET3 (38 lb/hr, 150 lb/hr), and ET4 (60 lb/hr, 225 lb/hr) yielded stack mercury

removals of 67.8%, 84.7%, 88.6%, and 91.1%, respectively. During the extended tests, no significant balance-of-plant effects were observed.

In addition to the mercury data, select U.S. Environmental Protection Agency (EPA) sampling methods were also carried out in order to assess balance-of-plant effects due to sorbent injection for mercury removal. EPA M26a sampling was conducted during baseline, DARCO Hg-LH, and SF10–SB24 ET1 test periods. The data show no significant increase in Cl and Br emissions due to sorbent and SEA–sorbent injection. EPA M29 sampling during baseline conditions indicated that >99% removal was obtained for all hazardous air pollutants (HAPs) (excluding Hg) on a coal to stack basis. During sorbent injection, a slight increase in removal was observed for some of the HAPs, and the removal for the other HAPs remained consistent with baseline values. EPA M5 sampling during baseline and SF10-SB24 ET1 test conditions indicated no significant increase in particulate emissions as a result of sorbent injection. The stack particulate values during baseline and SF10-SB24 ET1 test conditions were indistinguishable.

Parametric and brief extended testing of the alternate SEA technology demonstrated the feasibility of the technology as a promising mercury removal option in the near future. Mercury removals as high as 77.4% and 78.6% were obtained at the ID fan outlet and stack, respectively. An 8-hour extended test utilizing SC1–SB24 demonstrated consistent mercury removal which averaged 66.0% and 70.4% at the induced-draft fan outlet and stack, respectively.

TABLE OF CONTENTS

LIST OF FIGURES iii

LIST OF TABLES vi

NOMENCLATURE vii

EXECUTIVE SUMMARY ix

INTRODUCTION 1

BACKGROUND 3

PROJECT PARTICIPANTS 7

GOALS AND OBJECTIVES 9

DESCRIPTION OF TEST MATERIALS 11

DESCRIPTION OF TEST UNIT AND SAMPLING LOCATIONS 13
    SEA Injection Location 14
    Injection Location/Lance Design 15
    Injection Equipment 16

TEST COAL 17
    Discussion of Test Coal 17
    Mercury Variability in the Coal 18

TEST PLAN 21
    Flue Gas Sampling 23
        Continuous Mercury Monitors 23
        Sorbent Trap Sampling 24
        Trace Metal and Particulate Sampling 25
        Halogen Sampling 26
    Plant Data 28

TEST RESULTS 29
    Baseline Tests 29
    Parametric Tests 31
        Norit Americas Sorbents 31
        RLP Energy SEAs and Sorbents 32
    Extended Tests 38

Continued…

TABLE OF CONTENTS (continued)

BALANCE-OF-PLANT RESULTS....43
- Unit Performance....44
- ESP Ash Sampling....53
- Scrubber Hg Sampling....57
- Mass Balance....59
- Mercury....60
- HAPs....62
- Flue Gas Trace Metal Content....63
- Dust Loading....64
- Flue Gas Halogen Content....65
- Effects of TIFI^{TM} Injection....66
- Fly Ash Self-Heating....67

ALTERNATE SEA TESTING....69
- Alternate SEA Parametric Tests....70
- Alternate SEA Extended Test....71
- Comparison of Alternate SEA Technology....72
- Leaching Results....75

CONCLUSIONS....75

REFERENCES....77

TEST COAL DATA....Appendix A

CONTINUOUS MERCURY MONITOR DATA....Appendix B

SORBENT TRAP DATA....Appendix C

SAMPLE CALCULATIONS....Appendix D

U.S. ENVIRONMENTAL PROTECTION AGENCY
M26A, M29, AND M5 DATA....Appendix E

PLANT DATA....Appendix F

ELECTROSTATIC PRECIPITATOR DATA....Appendix G

ESP ASH DATA....Appendix H

SCRUBBER DATA....Appendix I

MASS BALANCE DATA....Appendix J

LEACHING RESULTS....Appendix K

LIST OF FIGURES

1 Mercury removal as a function of ACI rate, comparing coal ranks on ESP-only or ESP–sorbent–FF combination 4

2 Pilot-scale data showing the mercury removal of plain and treated/ enhanced carbon on an ESP-only configuration 5

3 Chemisorption model for mercury–flue gas interactions with sorbents 5

4 Effect of SO_2 (a) and NO_2 (b) concentrations on Hg^0 capture with AC 6

5 Schematic of Centralia Unit 2 13

6 Comparison of day-to-day mercury concentration in the test coals 19

7 Comparison of the inlet mercury flue gas concentrations based on ST data and as calculated from the mercury in coal 19

8 A schematic of the EPA Method 29 sampling train 26

9 Figure 9a (top) displays the September baseline CMM data; Figure 9b (bottom) displays the October baseline CMM data 30

10 ID fan outlet and stack percent mercury removals as a function of DARCO Hg-LH injection rates 31

11 ID fan outlet and stack percent mercury removals as a function of DARCO Hg-CC injection rates 32

12 DARCO Hg-CC mercury percent removal curves as a function of injection rate 33

13 ID fan outlet and stack percent mercury removals as a function of SF10 injection rates 34

14 ID fan outlet and stack percent mercury removals as a function of SF10–SB24 injection rates 35

15 ID fan outlet and stack percent mercury removals as a function of SF10–SB21 injection rates 35

16 ID fan outlet and stack percent mercury removals as a function of SF10–SB26 injection rates 36

Continued…

LIST OF FIGURES (continued)

17 ID fan outlet and stack percent mercury removals as a function of SF10–SB17 injection rates 37

18 Coal-to-stack and ST inlet-to-stack mercury removals during ET1 38

19 Coal-to-stack and ST inlet-to-stack mercury removals during ET2 39

20 Coal-to-stack and ST inlet-to-stack mercury removals during ET3 40

21 Coal-to-stack and ST inlet-to-stack mercury removals during ET4 41

22 Summary of SF10–SB24 extended test mercury removal data 42

23 Load during parametric testing 45

24 Load during extended testing 45

25 Load during alternate SEA testing 46

26 Flue gas temperatures during parametric testing 47

27 Flue gas temperatures during extended testing 47

28 Flue gas temperatures during alternate SEA testing 48

29 Air preheater differential pressures during parametric testing 48

30 Air preheater differential pressures during extended testing 49

31 Air preheater differential pressures during the alternate SEA test period 49

32 LC22 Field 1A, comparison of baseline and injection conditions 51

33 LC22 Field 2A, comparison of baseline and injection conditions 51

34 LC22 Field 3A, comparison of baseline and injection conditions 52

35 LC22 Field 4A, comparison of baseline and injection conditions 52

36 Baseline and ET3 mercury in ash concentration in the Koppers and Lodge ESPs 55

Continued…

LIST OF FIGURES (continued)

37 Baseline and ET3 total Cl and Br in ash concentration in the Koppers and Lodge ESPs... 55

38 Baseline and ET3 ash LOI data for the Koppers and Lodge ESPs 56

39 Baseline and ET3 scrubber Hg data 58

40 Mercury removal across each pollution control device 61

41 Effects of TIFI injection on sorbent injection for mercury removal 66

42 Self-heating risk plot based on an O_2 concentration of 6% and a surrounding ambient temperature of 70°F 67

43 Alternate SEA injection schematic 69

44 ID fan outlet and stack percent mercury removals as a function of SC1–SB24 injection rates.. 70

45 SC1–SB24 extended test CMM data 71

46 Summary of alternate SEA injection results compared to other technologies tested.......... 72

LIST OF TABLES

1 Mercury Removal as a Function of Coal Type and Plant Configuration 3

2 Sorbents–Additives Injected During the Test Project 11

3 Average Properties of Test Coal 17

4 Uncontrolled Flue Gas Mercury Concentration Data Based on Average Coal Analysis Results and EPA M19 Calculations 18

5 Comparison of Monthly Average Uncontrolled Flue Gas Mercury Concentration Data ... 18

6 Monthly Comparison of ST and Uncontrolled Flue Gas Mercury Data 22

7 Test Schedule 22

8 Extended Test Mercury Removals at the ID Fan Outlet 41

9 Extended Test Mercury Removals at the Stack 41

10 Plant Data Monthly Averages 44

11 Lodge Cottrell Operational Data 50

12 Cl and Br, Hg, and LOI ESP Data During the September Baseline Test Period 53

13 Cl and Br, Hg, and LOI ESP Data During ET1, ET2, and ET3 54

14 Baseline Mercury Analysis for Scrubber Reagent Feed, Recycle Slurry, and Gypsum 57

15 Mercury Analysis for Scrubber Reagent Feed, Recycle Slurry, and Gypsum During ET1, ET2, and ET3 57

16 Mercury Mass Balance for the Test Unit 60

17 HAP Mass Balance for the Test Unit 62

18 Baseline EPA Method 29 Test Results 63

19 SF10–SB24 ET1 EPA Method 29 Test Results 63

20 EPA M5 Dust Loading Data 64

21 EPA Method 26a Test Results 65

22 Sorbent Content in Ash 68

23 TCLP Limits and Maximum Leachate Concentrations for Select HAPs........................... 73

NOMENCLATURE

AC	activated carbon
ACI	activated carbon injection
AH	air heater
APCD	air pollution control device
ASTM	ASTM International
BOP	balance of plant
CCME	Canadian Council of Ministers of the Environment
CE	Combustion Engineering
CMM	continuous mercury monitor
CVAAS	cold-vapor atomic absorption spectroscopy
CVAFS	cold-vapor atomic fluorescence spectrometry
DOE	U.S. Department of Energy
dscf	dry standard cubic feet
EERC	Energy & Environmental Research Center
EPA	U.S. Environmental Protection Agency
ESP	electrostatic precipitator
ET	extended test
FF	fabric filter
gr	grains
HAP	hazardous air pollutant
ICR	information collection request
ID	induced draft (fan)
LAC	lignite activated carbon
LOI	loss on ignition
NIST	National Institute of Standards and Technology
NODA	notice of data availability
PRB	Powder River Basin
QA/QC	quality assurance/quality control
SEA	sorbent enhancement additive
SSTP	site-specific test plan
ST	sorbent trap
std. dev.	standard deviation
WFGD	wet flue gas desulfurization (unit)

FULL-SCALE TESTING TO EVALUATE MERCURY CONTROL OPTIONS AT THE CENTRALIA GENERATING STATION

EXECUTIVE SUMMARY

In North America, testing has been under way at coal-fired electric power plants to find viable and economical mercury control strategies to meet pending regulations. TransAlta Centralia Generation, LLC, along with the U.S. Department of Energy (DOE) contracted with the University of North Dakota's Energy & Environmental Research Center (EERC) to evaluate sorbent-based mercury control technologies at TransAlta's coal-fired Centralia Generating Station. The primary goal was to identify sorbent-based technology options that could be used to meet an overall mercury removal goal of ≥ 80%.

The EERC has successfully pilot- and field-tested several sorbent-based technologies that offer promise and potential to achieve the mercury removal goal of ≥ 80%. Based on these pilot- and field-scale test results, the EERC proposed research tests to evaluate potential sorbent-based technologies provided by RLP Energy and Norit Americas that could potentially meet TransAlta's mercury control objectives. Tests were performed at TransAlta's Centralia Unit 2, 688 MW (net output), which burns a Powder River Basin subbituminous coal supplied via train. Average coal composition based on belt grab samples are shown in Table ES-1. From August through October 2009, the EERC evaluated a sorbent enhancement additive (SEA), SF10, alternative SEA sorbents (SC1, SC3, and SC6), and numerous proprietary sorbents provided by RLP Energy, as well as Norit's DARCO® Hg-LH and DARCO Hg-CC (concrete-friendly) mercury sorbents. SF10 was injected into the burner front of the west side of the furnace, and the back-end sorbents were injected into the ducts between the two electrostatic precipitators (ESPs) on both the north and south sides. The alternative SEAs were injected upstream of the sorbent injection.

Elemental and total gaseous mercury concentrations were measured with a continuous mercury monitor (CMM) temporarily installed at the Lodge (second ESP) inlet and induced-draft fan outlet located on the south side of the test unit. A plant CMM, located at the stack, was also used. A sorbent trap (ST) method (similar to U.S. Environmental Protection Agency [EPA] Method 30B) was also used to sample and measure total vapor-phase mercury concentrations periodically at each sampling location.

Baseline testing was performed for 3 days to evaluate the variability in flue gas mercury concentrations and the inherent mercury removal performance of the unit. The average total mercury concentration obtained from ST measurements at the Koppers (first ESP) inlet was 10.48 μg/dNm^3 at 3% O_2. During baseline testing conditions, average ST data from the Koppers inlet and stack indicated an overall native mercury removal efficiency of approximately 18.5%.

Parametric tests were performed by injecting SF10 into the burner front of the furnace coupled with select sorbents injected between the two ESPs. Several SF10 and sorbent combinations showed promise and were able to achieve ≥ 80% mercury removal, albeit at varying rates of each material. Based on the results of these tests, the best combination—

Table ES-1. Average Properties of Test Coal, As-Received Basis, Unless Otherwise Noted

Parameter	Average[a]	Std. Dev.[b]
Hg, ppm (dry basis)	0.078	0.013
Total Cl, Br, and I,[c] ppm (dry basis)	29.2	30.2
Proximate Analysis, wt%		
Moisture	31.16	1.58
Volatile Matter	25.08	0.95
Fixed Carbon	39.34	1.42
Ash	4.42	1.26
Ultimate Analysis, wt%		
Hydrogen[d]	3.17	0.15
Carbon	48.64	1.45
Nitrogen	0.60	0.03
Sulfur	0.31	0.06
Oxygen[d]	11.69	0.41
Heating Value, Btu/lb	8111	238

[a] Based on 53 coal sample analyses.
[b] Standard deviation.
[c] Value does not include fluorine.
[d] Moisture not included in hydrogen and oxygen values.

SF10–SB24—was selected for extended testing because it exhibited the greatest mercury removal at the smallest injection rates of materials. Following the parametric tests, four extended tests using SF10–SB24 were conducted for approximately 5 days each, with mercury removals targeted at 60%, 70%, 80%, and >90%.

The results of the extended tests are shown in Figure ES-1. The figure shows that each test was able to achieve the target mercury removal over several days of operation. The majority of the mercury removal occurs across the Lodge ESPs, with approximately an additional 10% across the wet flue gas desulfurization (WFGD) unit. The extended tests show that consistent mercury removal, at targeted removal amounts, was achieved for the periods tested. Maintaining a mercury removal of ≥ 80% over time at reasonable injection rates appears achievable based on these test results. The extended test data also show that 90% mercury removal is achievable, albeit at much higher injection rates. Longer-term testing will be required to verify that 90% removal can be sustained.

Figure ES-2 summarizes the test results for the best-performing technologies tested at the unit. The data in Figure ES-2 is a compilation of the parametric and extended test data for each technology. Of the four technologies, SF10–SB24 is able to achieve 60%, 70%, 80%, and 90% mercury removals at the lowest injection rates. SF10–SB24 was the only technology to demonstrate >90% mercury removal at the injection rates tested. All of the technologies depicted in Figure ES-2 were able to obtain >60% mercury removal.

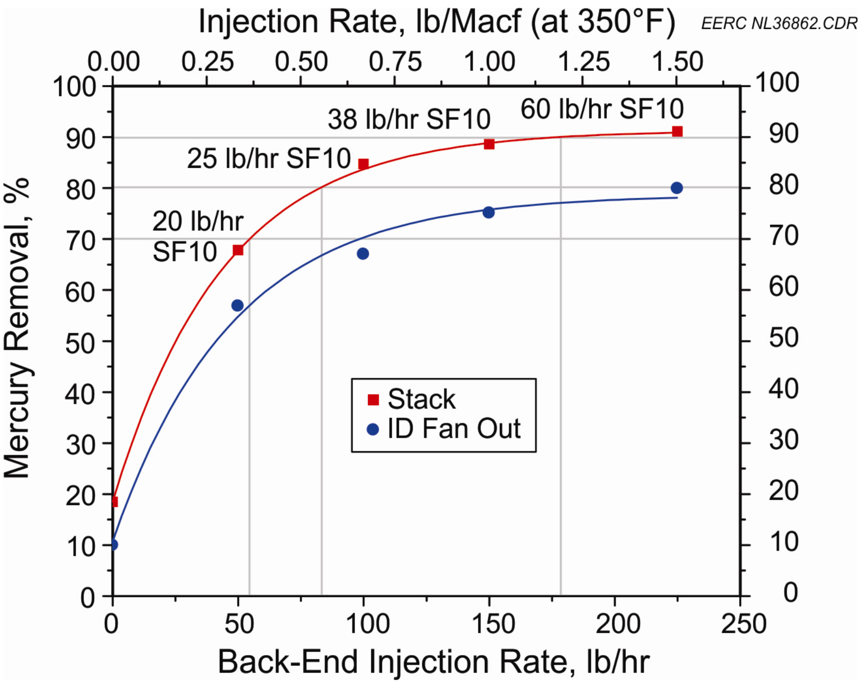


Figure ES-1. Summary of SF10–SB24 extended test mercury removal data. The injection rates arkime for the entire unit.

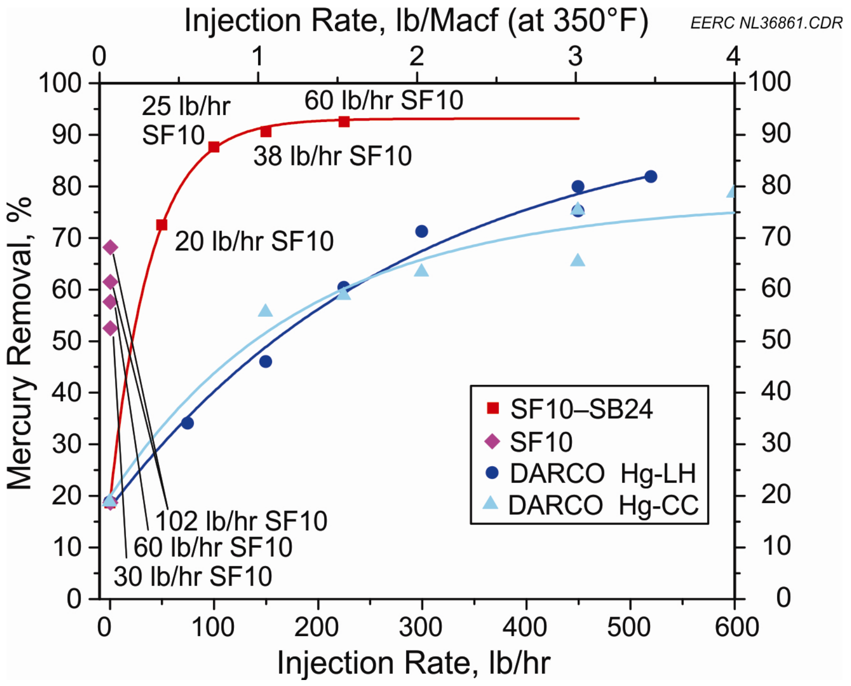


Figure ES-2. Summary of mercury removal results for the four best technologies. Injection rates are for the entire unit.

In addition to the mercury data, select EPA sampling methods were also carried out in order to assess balance-of-plant effects because of sorbent injection for mercury removal. EPA measurement of halogens using M26a sampling was conducted during baseline, DARCO Hg-LH, and SF10–SB24 ET1 test periods. The data show no significant increase in Cl and Br and F emissions because of sorbent and SEA–sorbent injection. EPA M29 sampling during baseline conditions indicated that >99% removal was obtained for all hazardous air pollutants (HAPs) (excluding Hg) on a coal to stack basis. During sorbent injection, a slight increase in removal was observed for some of the HAPs, and the removal for the other HAPs remained consistent with baseline values. EPA M5 sampling during baseline and SF10–SB24 ET1 test conditions indicated that there was no significant (positive or negative) change in particulate emissions as a result of sorbent injection. The stack particulate values during baseline and SF10–SB24 ET1 test conditions were indistinguishable.

Parametric and brief extended testing of the alternate SEA technology demonstrated the feasibility of the technology as a promising mercury removal option in the near future. Mercury removals as high as 77.4% and 78.6% were obtained at the induced-draft (ID) fan outlet and stack, respectively. An 8-hour extended test utilizing SC1-SB24 demonstrated consistent mercury removal which averaged 66.0% and 70.4% at the ID fan outlet and stack, respectively. Figure ES-3 displays the alternate SEA injection results along with some of the other technologies that were tested. The figure shows that the alternate SEA mercury removal results are much higher than the activated carbon (AC) mercury removals at equivalent injection rates. At equivalent injection rates, the SC1–SB24 and SC3–SB24 mercury removal results are approximately 10% lower than the SF10-SB24 mercury removal results. This shows that the alternate SEA technology performs much better than treated AC, but in its current state of operation is not quite as effective as the best SEA–sorbent technologies tested. Further improvements on design and operation of the alternate SEA are expected to improve on these results.

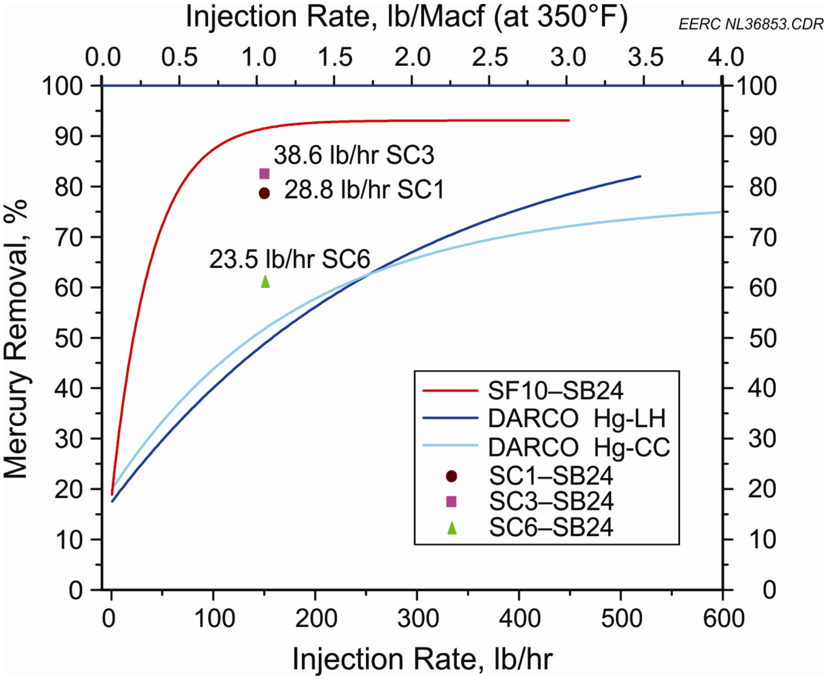


Figure ES-3. Summary of alternate SEA injection results compared to other technologies tested. Note: SC3–SB24 mercury removal was increased by 5% to reflect stack mercury removals. Injection rates are for the entire unit.

FULL-SCALE TESTING TO EVALUATE MERCURY CONTROL OPTIONS AT THE CENTRALIA GENERATING STATION

INTRODUCTION

In North America, testing has been under way at coal-fired electric power plants to find viable and economical mercury control strategies to meet pending regulations. TransAlta Centralia Generation, LLC, along with the U.S. Department of Energy (DOE) contracted with the University of North Dakota's Energy & Environmental Research Center (EERC) to evaluate sorbent-based mercury control technologies at TransAlta's coal-fired Centralia Generating Station. The primary goal was to identify sorbent-based technology options that could be used to meet an overall mercury removal goal of ≥ 80%.

To achieve this mercury removal goal, an intensive project was initiated in August 2009 to evaluate several mercury control options at TransAlta's Centralia Generating Station. This test program included evaluation of RLP Energy's synergistic sorbent enhancement additive (SEA)–sorbent injection technology approach, an alternative SEA technology, and activated carbon (AC) sorbents provided by Norit Americas. The station is located near Centralia, Washington, and currently has two units in operation; testing was conducted on Unit 2, which has a gross output of 730 MW. Each of the units has identical tangentially fired boilers manufactured by Combustion Engineering (CE). Particulate matter is captured on each unit by four cold-side electrostatic precipitators (ESPs), arranged in two sets in series. A wet flue gas desulfurization (WFGD) unit follows the ESPs for the control of SO_2 emissions. Unit 2 combusts a Powder River Basin (PRB) subbituminous coal which is transported to the plant via rail.

From August through October 2009, the EERC evaluated one RLP Energy SEA, SF10, coupled with numerous proprietary sorbents, an alternative SEA, and Norit America's DARCO® Hg-LH and DARCO Hg-CC.

RLP Energy's SF10 was injected into the front of the burner of the west side of the furnace, and sorbents were injected in between the two ESPs. Several SF10–sorbent combinations were evaluated under parametric conditions to determine the technology combination(s) that could achieve the target mercury removal goal of ≥ 80%. The most promising combination, SF10–SB24, was then tested at various injection rates for 20 days on a continuous 24-hour basis.

Percent mercury removals were calculated based on mercury measurements of the coal, the flue gas at the Koppers inlet, induced draft (ID) fan outlet, and flue gas at the stack of Unit 2.

BACKGROUND

Over the last 15 years, the EERC has worked with utilities in both the United States and Canada to address mercury control options. Since the U.S. Environmental Protection Agency (EPA) announced its intention to regulate mercury in 2000, utilities have been assessing options for mercury control. Although several control strategies have been devised and tested, sorbent-based technologies have been identified as the most mature, consistent, and economical strategy for mercury removal. During early testing, both in Canada and the United States, it became apparent that coal rank and utility configuration were two of the biggest factors affecting the possible removal of mercury, as indicated in Table 1 and Figure 1.

Presented in Figure 1 are results from various full-scale tests that were performed in the United States and Canada, indicating a clear difference between what can be achieved with activated carbon injection (ACI) with different ranks of coal using either an ESP or an ESP–sorbent–fabric filter (FF) combination (referred to as a TOXECON™ system in the United States).

The EERC has been working with several sponsors across both the United States and Canada to evaluate many sorbent-based mercury control options. Over the last 10 years, these projects have ranged from bench- to full-scale tests to evaluate various sorbents for mercury control that can be applied to low-chlorine-content, low-rank coals, which frequently show a high fraction of elemental mercury in the flue gas, making mercury capture challenging.

Earlier in this decade, the Canadian government initiated a data-gathering process to evaluate mercury control options, under which the Canadian Council of Ministers of the Environment (CCME) requested that the EERC provide a technical review of mercury control technologies applicable to coal-fired power plants in Alberta, Manitoba, New Brunswick, Nova Scotia, and Saskatchewan (1). The EERC report to CCME evaluated the maturity, commercial availability, effectiveness, and relative economy of various mercury control technologies appropriate for each power plant. The information in that report showed that sorbent control technologies are presently among the most effective and economical for implementation. Several

Table 1. Mercury Removal as a Function of Coal Type and Plant Configuration

	Mercury Removal Efficiencies, %[a]			
Control Technology	Bituminous	Subbit.	Lignite	All Coals
Cold-Side ESP	30–40	0–20	0–10	0–40
Cold-Side ESP + Wet FGD	60–80	15–35	0–40	0–80
Dry FGD + Cold-Side ESP	35–50	10–35	0–10	0–50
FF	40–90	20–75	0–10	0–90
FF + Wet FGD	75–95	30–75	10–40	10–95
Dry FGD + FF	65–95	20–40	0–20	0–95
Coal Cleaning	20–40			0–40

[a] Ranges based on data from EPA notice of data availability (NODA), information collection request (ICR) data, field tests, and observations. Some values are based on single data points and may not reflect removal for all plants. Data are based on U.S. plants and the coals typically burned.

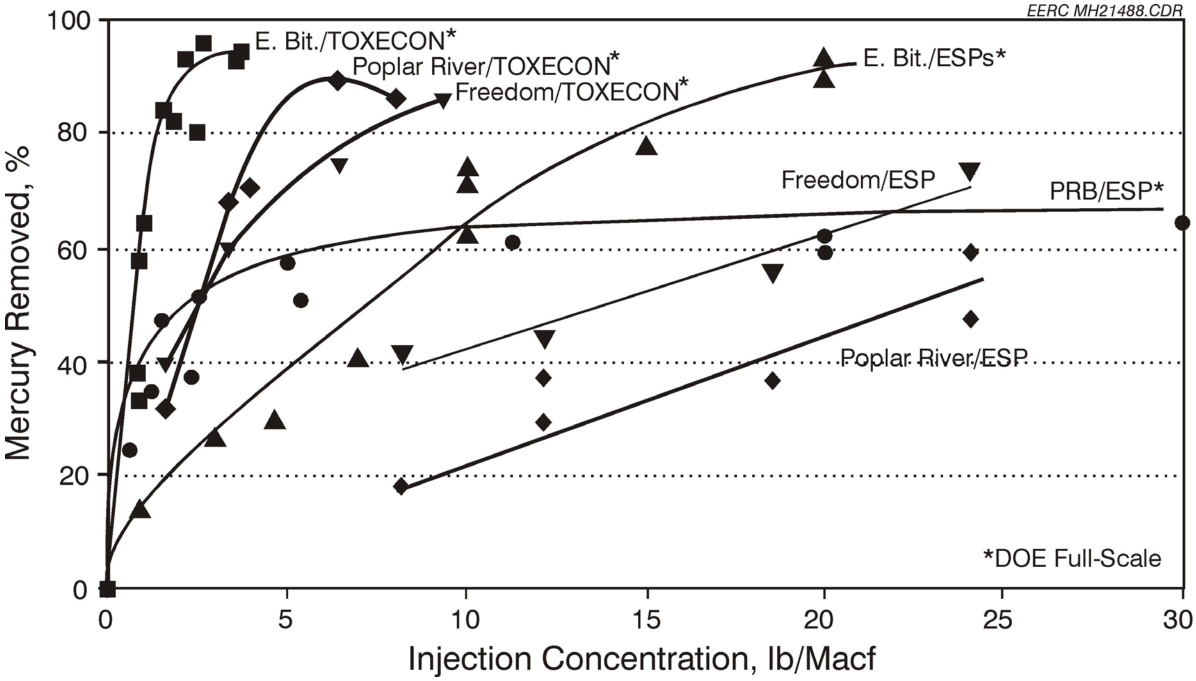


Figure 1. Mercury removal as a function of ACI rate, comparing coal ranks on ESP-only or ESP–sorbent–FF combination.

other reports have been issued by various parties that underscore this position. Until further development is done, sorbent-based technologies are among the easiest technology to implement, with the least disruptive changes to the unit and with the best understood impacts.

The CCME report, as well as many other research projects, indicated that technologies that can enhance mercury capture through the use of SEAs or treated ACs should be considered and evaluated as an approach to control mercury emissions. Several economic analyses have shown that the sorbent cost is the largest ongoing factor when sorbent injection is used as a mercury control strategy. Additives and/or treatments, as shown in Figure 2, can be used to lower the total amount of injected material, while often promoting mercury capture at a reduced cost. If these technologies can lessen the total amount of sorbent injected, utility by-product sales may also be maintained, thereby preserving a valuable revenue stream and lessening the amount of material to be landfilled.

Through extensive research, the EERC has developed a complex mercury–sorbent–flue gas interaction model, shown in Figure 3, that shows the role and impact that various flue gas components have on chemisorption (2). This figure, along with Figure 4, shows that acid gas constituents play a large role in mercury sorption. When either SO_2 or NO_2 is absent, mercury adsorption by the sorbents occurs for over 10 hr. However, when SO_2 and NO_2 are present, even at low concentrations, mercury sorption is greatly reduced to less than 5 hr, significantly lowering the mercury capture capacity of the sorbents. The combination of SO_2 and NO_2 strongly suggests that SO_3 competes for the same sorption sites as mercury. However, the SO_3 exists in

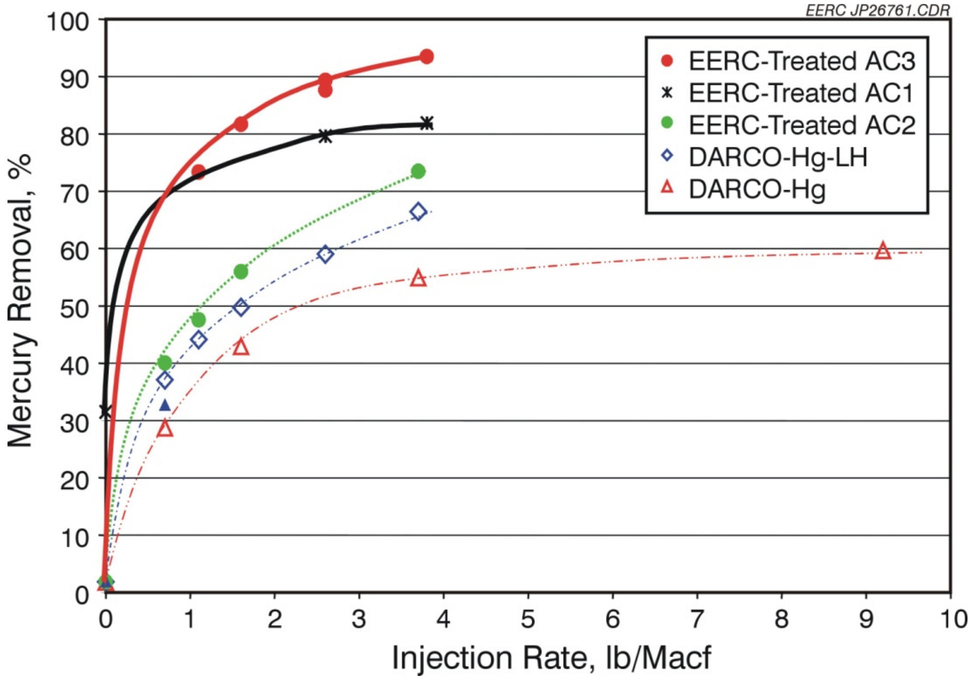


Figure 2. Pilot-scale data showing the mercury removal of plain and treated/enhanced carbon on an ESP-only configuration.

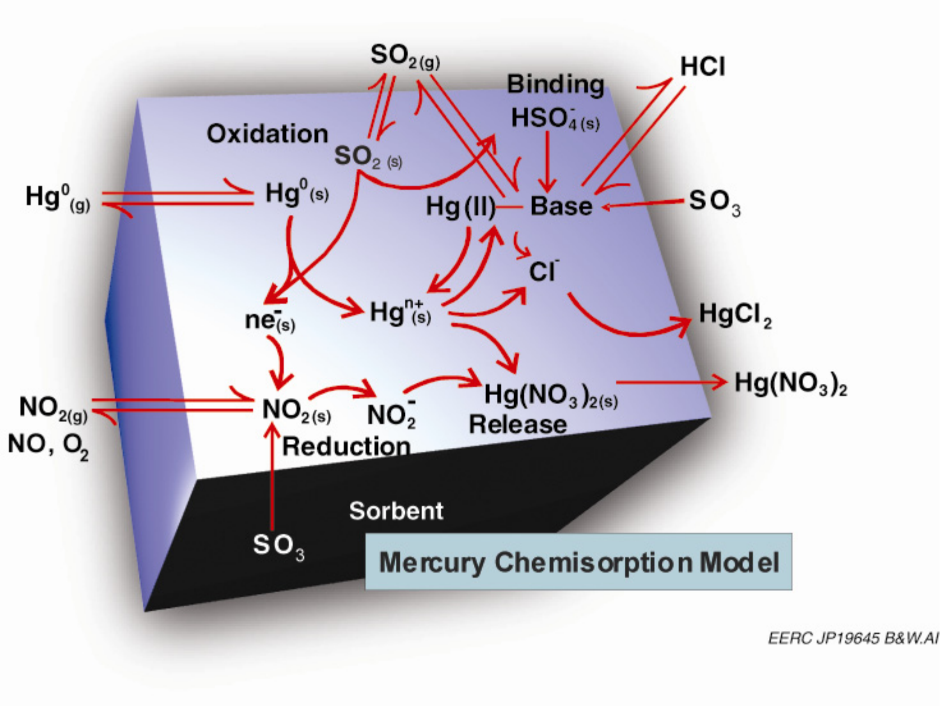
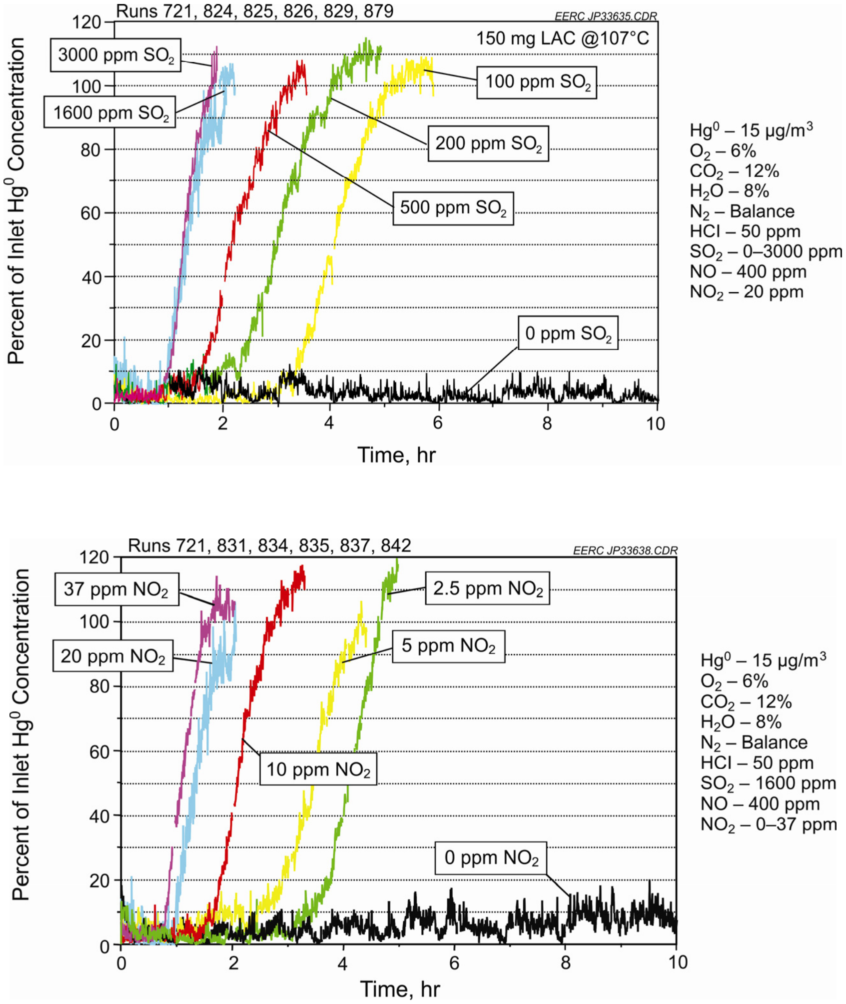


Figure 3. Chemisorption model for mercury–flue gas interactions with sorbents.



(a)

(b)

Figure 4. Effect of SO_2 (a) and NO_2 (b) concentrations on Hg^0 capture with AC (LAC = lignite activated carbon).

much higher concentrations than mercury, enabling it to consume more of the sorption sites than mercury.

The EERC model further shows that mercury oxidation, whether it occurs homogeneously (i.e., in the gas phase) or heterogeneously on/within the sorbent structure, must occur before the basic sites can chemisorb the mercury. The basis of this model provides much insight into why the mercury must be oxidized, how to enhance mercury oxidation on the sorbent by the use of SEAs, and how NO_x and SO_x (SO_2 and SO_3) hinder mercury capture. For example, for low-chlorine coals that produce predominantly elemental mercury, an enhancing agent such as a halogen is needed to promote oxidation of the mercury on/within the sorbent, which is then subsequently captured on basic sites within the sorbent structure. In contrast, for coals that produce significant SO_3 concentrations, the SO_3 will bind to the basic sites preferentially, limiting the sites available for mercury chemisorption. This is of significant importance when SO_3 injection is used to condition fly ash to improve ESP collection.

PROJECT PARTICIPANTS

To execute the project, several organizations were involved, requiring a very collaborative approach. Their roles in the project are briefly described below:

- TransAlta – Assembled project team and contracted organizations to perform research project, managed corporate and plant activities and communications, and interfaced with and directed project team.

- Centralia Generating Station – Owned and operated by TransAlta. Served as host site for tests.

- DOE – The project was performed under an existing EERC–DOE Joint Program on Research and Development for Fossil Energy-Related Resources. The objective is to advance the deployment of advanced technologies for improving energy efficiency and environmental performance through jointly sponsored research.

- EERC – U.S.-based research, development, demonstration, and commercialization organization. Contracted by TransAlta to serve as project lead. Oversaw and managed research program; provided test, injection, and measurement equipment; and coordinated and performed tests, data reduction, and reporting.

- RLP Energy – A commercial vendor supplying long-term equipment, materials, and services to power utilities. Provided SEA, alternative SEA, and proprietary test sorbents. Assisted in on-site test activities related to their material and equipment.

- Norit Americas, Inc. – A commercial provider of ACs and portable injection skids; provided (through purchase) the supply of DARCO Hg-LH and DARCO Hg-CC sorbents.

GOALS AND OBJECTIVES

The primary project goal was to identify and evaluate the most promising technology options that could be used to meet the targeted mercury removal of ≥ 80%. To accomplish this goal, a SEA coupled with several sorbents provided by RLP Energy was tested, along with Norit Americas sorbents. A suite of alternative SEA technologies were also tested. The specific objectives of field testing activities were to gather data (technology effectiveness, etc.), guide future test decisions, and support development of a mercury control strategy. The following objectives were achieved through testing:

- Performed testing on Centralia Unit 2 in order to obtain verifiable results.

- Evaluated back-end-only sorbents and combined front-end SEA injection coupled with back-end sorbent injection for their ability to attain a mercury removal goal of ≥ 80%.
- Compared CMM results to sorbent trap (ST) results to evaluate the reliability of mercury measurements.

- Calculated ESP and stack mercury removal efficiencies from coal mercury concentrations and ST method and continuous mercury monitor (CMM) measurements at the ESP outlet.

To meet the overall project goal, the EERC and RLP Energy identified the following pretest objectives and activities to adequately prepare for the test program:

- EERC and RLP Energy personnel conducted a site visit to assess potential sorbent injection locations, site needs, and possible impediments to testing.

- A site-specific test plan (SSTP) was prepared by the EERC with the guidance and assistance of TransAlta that included baseline, parametric, and extended testing of several mercury control options, including an SEA plus a variety of proprietary sorbents.

- A temporary sorbent injection system was installed to inject between the two ESPs. In addition, a feeder was installed to inject an SEA into the furnace adjacent to the burners.

Testing activities included the following:

- A SSTP was prepared, updated, and submitted to all team members as needs evolved over the course of testing.

- To obtain mercury concentration data at various locations within the unit, CMMs were temporally installed at the Lodge inlet (second ESP), at the ID fan outlet, and in the stack.

- ST sampling and analyses were used to evaluate and compare CMM results.

- On-site mercury analysis of ST samples was conducted in the EERC’s mobile laboratory to evaluate mercury removals quickly and to direct ongoing testing decisions.

- Coal and ash samples were obtained and analyzed off-site to support the evaluation of mercury removals.

- Extended parametric tests were conducted using carbon- and non-carbon-based sorbents coupled with the SF10 SEA to obtain data regarding an optimal ratio to meet and, at times, exceed the mercury removal target.

- Quality measures were implemented to ensure accurate measures of mercury in coal, fly ash, and flue gas to accurately evaluate mercury removals.

DESCRIPTION OF TEST MATERIALS

One SEA, three alternate SEAs, and four sorbents provided by RLP Energy were tested on-site. Two Norit Americas sorbents were also tested. The sorbents tested at Centralia Unit 2 are listed in Table 2.

Table 2. Sorbents–Additives Injected During the Test Project

Material	Vendor	Product Base Type
SF10	RLP Energy	Noncarbon SEA
SB17	RLP Energy	Non-carbon-based sorbent
SB21	RLP Energy	Carbon-based sorbent
SB24	RLP Energy	Carbon-based sorbent
SB26	RLP Energy	Non-carbon-based sorbent
SC1	RLP Energy	Alternate SEA
SC3	RLP Energy	Alternate SEA
SC6	RLP Energy	Alternate SEA
DARCO Hg-LH	Norit Americas	Carbon-based sorbent
DARCO Hg-CC	Norit Americas	Carbon-based sorbent

DESCRIPTION OF TEST UNIT AND SAMPLING LOCATIONS

Centralia Generating Station is owned by TransAlta Corporation and is located near Centralia, Washington. The station consists of two 688-MW (net) units for a net generation capacity of approximately 1376 MW. Each of the units has identical tangentially fired boilers manufactured by CE. Each unit is equipped with low-NO_x burners and has overfire air to reduce NO_x emissions. Particulate matter is controlled on each unit by four cold-side ESPs—two parallel sets of two ESPs in series. Sulfur emissions are controlled on each unit by a scrubber. A schematic of Unit 2 that shows sampling and injection locations is presented in Figure 5.

In order to determine the mercury removal across each air pollution control device (APCD), sampling was conducted at four locations, including the Koppers inlet, Lodge inlet, ID fan outlet, and stack. All of the sampling was conducted on the south side of the test unit rather than both sides of the unit in order to reduce project costs. STs were collected at each sampling location, and CMMs were installed at the Lodge inlet, ID fan outlet, and stack locations. EPA Method 26a (M26a) and M29 sampling was conducted at both the Lodge inlet and stack-sampling locations.

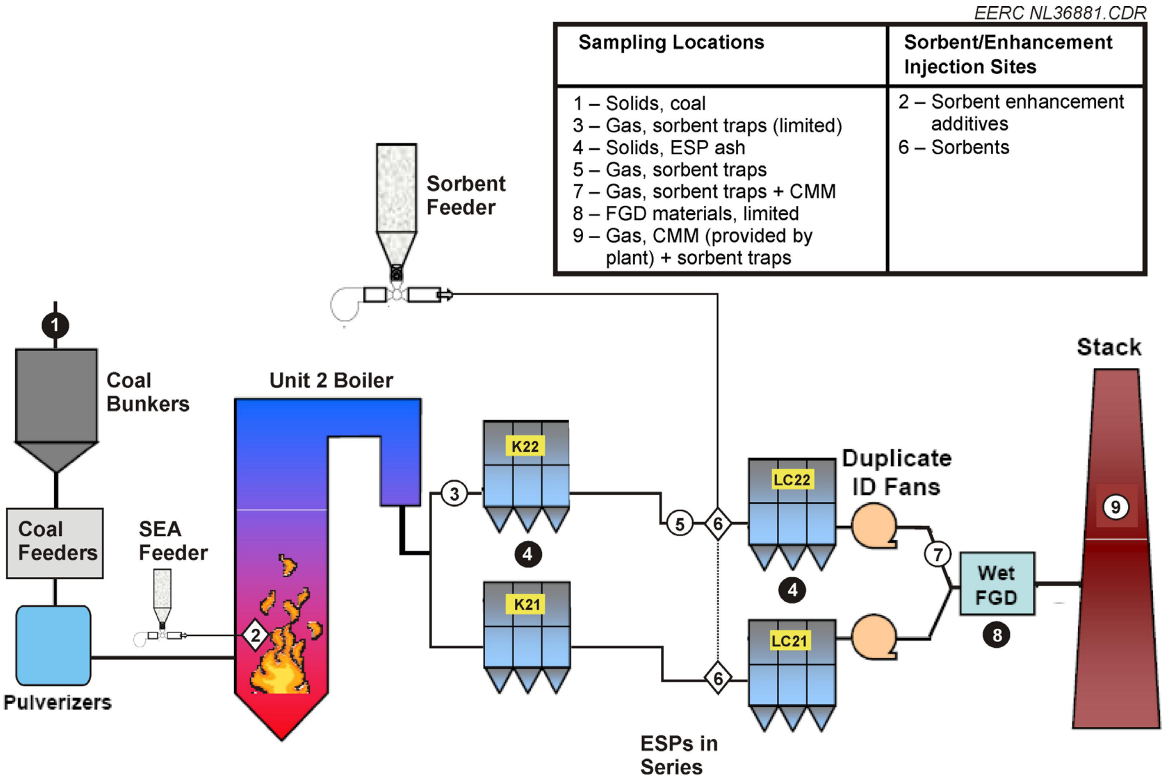


Figure 5. Schematic of Centralia Unit 2.

SEA Injection Location

The injection of SEA was accomplished with an EERC-supplied feeder placed at the sixth-floor elevation of the boiler. All injection occurred on the west side of the boilers next to the division wall separating the two halves of the furnace on Unit 2. The feed line was raised up to the seventh-floor level where a “Y” connection split the injection hose. The SEA was injected via lances inserted through modified furnace observation ports. The injection lances had an outer diameter of 2.54 cm (1 inch) and were approximately 1.5 feet long. The feeder was calibrated on-site before the injection tests began. The alternate SEA testing is discussed in a separate section later in the report.

Injection Location/Lance Design

In order to ensure proper sorbent distribution and mixing in the ductwork, care was taken in choosing an adequate injection location and lance design. The injection location chosen was the ductwork between the Koppers and Lodge ESPs. This ductwork at this location has a fairly straight run on either side. Based on the ductwork, it is likely that the flow is laminar in this section. Downstream of this location, the ductwork changes directions many times before it enters the Lodge ESP. These changes in direction facilitate sorbent mixing in the flue gas.

Once the injection location was determined, the lances were designed. The lances were designed to provide adequate distribution in the duct and to take advantage of the subsequent mixing provided by the bends in the ductwork. The lances were all constructed of 1-in. tubular stainless steel pipe. The lances were 12 ft in length and had two holes, one at 6 ft and one at the end of the lance. At the 6-ft location, the lance was cut in half lengthwise, and a plate was added to the remaining 6 ft of the lance. By splitting the pipe, the flow distribution at the 6-ft and 12-ft locations is equal.

Injection Equipment

SEA furnace injection was carried out with an EERC-provided injection system consisting of a screw feeder with a 200-lb capacity hopper. The SEA was carried to the injection lances by use of an eductor connected to an air supply. One transport line was used to convey the material to a “Y” where the SEA was evenly split to the two lances. After installation, a calibration curve was generated for the system. The system was able to operate in either volumetric or loss-in-weight mode. To operate, the system is powered and simply given a set point based on the calibration curve. During operation, a log book was kept, and the system was checked every 30 to 60 min. The hopper was refilled manually, as needed, with material from 60-lb totes.

Sorbent injection was performed with a feed system originally designed and manufactured by Nol-Tec. The system was subsequently modified prior to the start of this project. The system utilized a screw feeder to feed the material into an eductor, which conveyed the material in a 3-in. hose to a “Y” connection via a roots-type blower. From the “Y” connection, the sorbent was conveyed to the north and south sides of the unit by 2.5-in. hoses. At the duct, a six-way splitter evenly split the sorbent into 1-in. hoses that were connected to the lances used to introduce the sorbent into the duct. The system was capable of using either 1000-lb sacks or was able to accept sorbent from an EERC-provided silo.

TEST COAL

Discussion of Test Coal

During the test program, coal samples were taken by plant personnel twice daily from the coal belt. The coal is sampled from the belt via an ASTM International (ASTM) automated sampler. The sampling plan was created and approved by plant personnel before the test program began and is shown in Appendix A. Fifty-three composite coal samples were analyzed for Hg, Cl, proximate–ultimate, and Btu analyses using standard ASTM or EPA methods. Proximate and ultimate analyses were conducted on the coal samples using ASTM Methods D3172, D5142, and D3176. A Mitsubishi Model TOX-100 total chlorine analyzer was used to perform ASTM Method D6721-01 (Standard Test Method for Determination of Chlorine in Coal by Oxidative Hydrolysis Microcoulometry). Coal mercury content was determined using cold-vapor atomic absorption spectroscopy (CVAAS) according to EPA Method 245.1 and EPA SW-846 Method 7470.

Results of the coal analyses are shown in Table 3. The data indicate that the test coal remained fairly stable even though the coal came from up to four different mines. The low standard deviations indicate that the coal sources are similar and consistent in composition. All coal analyses are provided in Appendix A.

Table 3. Average Properties of Test Coal, as-received basis, unless otherwise noted

Parameter	Average[a]	Std. Dev.[b]
Hg, ppm (dry basis)	0.078	0.013
Total Cl, Br, and I,[c] ppm (dry basis)	29.2	30.2
Proximate Analysis, wt%		
Moisture	31.16	1.58
Volatile Matter	25.08	0.95
Fixed Carbon	39.34	1.42
Ash	4.42	1.26
Ultimate Analysis, wt%		
Hydrogen[d]	3.17	0.15
Carbon	48.64	1.45
Nitrogen	0.60	0.03
Sulfur	0.31	0.06
Oxygen[d]	11.69	0.41
Heating Value, Btu/lb	8111	238

[a] Based on 53 coal sample analyses.
[b] Standard deviation.
[c] Value does not include fluorine.
[d] Moisture not included in hydrogen and oxygen values.

Mercury Variability in the Coal

The average mercury concentration, variability of the coal mercury concentration measured, and calculations of mercury concentrations on a flue gas basis and heating value basis are presented in Table 4. The ultimate analysis along with the mercury data were used to calculate the uncontrolled mercury concentrations in the flue gas using a calculation similar to the calculations found in EPA M19. The data presented in Table 4 show that the mercury exhibited some variance but, overall, remained fairly constant throughout the project test period based on the standard deviations.

Table 5 displays the uncontrolled flue gas mercury concentration for the months of August, September, and October. The mercury concentrations exhibited a slight decrease from August to September to October, but the data are within the standard deviation presented in Table 4. The table shows that the mercury concentration remains fairly stable on a monthly basis.

Table 4. Uncontrolled Flue Gas Mercury Concentration Data Based on Average Coal Analysis Results and EPA M19 Calculations

Parameter	Average	Std. Dev.
Hg, ppm (in coal, dry basis)	0.078	0.013
Hg, µg/dNm^3, 3% O_2 (from coal uncontrolled)	9.01	1.56
Hg, lb Hg/TBtu (from coal uncontrolled)	6.58	1.13

Table 5. Comparison of Monthly Average Uncontrolled Flue Gas Mercury Concentration Data

Parameter	August	September	October
Hg, ppm (in coal, dry basis)	0.082	0.078	0.075
Hg, µg/dNm^3, 3% O_2 (from coal uncontrolled)	9.67	8.94	8.74
Hg, lb Hg/TBtu (from coal uncontrolled)	6.99	6.55	6.41

Figure 6 plots the daily coal mercury values obtained from the coal samples taken from the coal belt. In order to determine the mercury concentration in the coal samples, an acid-leaching procedure was used followed by analysis using CVAAS. The average concentration for the samples was 0.078 ppm, with a standard deviation of 0.013 ppm. Although more than one coal was fired, the mercury values were fairly consistent in the differently mined coals.

Figure 7 plots the inlet flue gas mercury concentrations and the calculated flue gas mercury concentrations based on the mercury-in-coal concentrations. The ST averages represent a 1-hr average flue gas measurement, and the coal value represents a 12-hr coal average, which is representative of the coal to be fired during the daytime period of each day. The two independent measurements correlate fairly consistently for the duration of the test period. The range for the flue gas mercury concentration based on mercury-in-coal values was 6.18 µg/dNm^3 at 3% O_2 to 13.65 µg/dNm^3 at 3% O_2. This is consistent with the ST measured mercury range of 6.05 µg/dNm^3 at 3% O_2 to 13.99 µg/dNm^3 at 3% O_2.

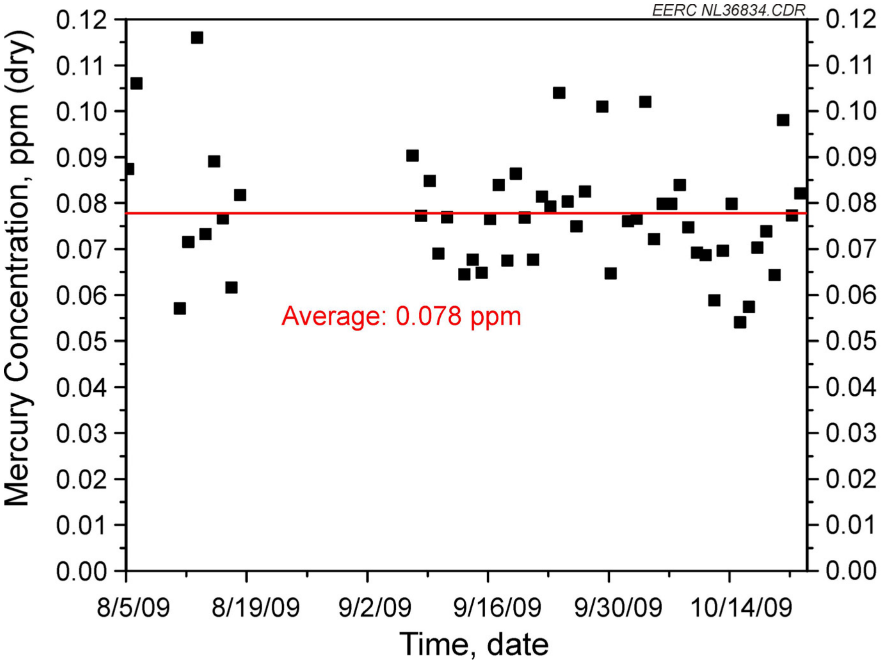


Figure 6. Comparison of day-to-day mercury concentration in the test coals.

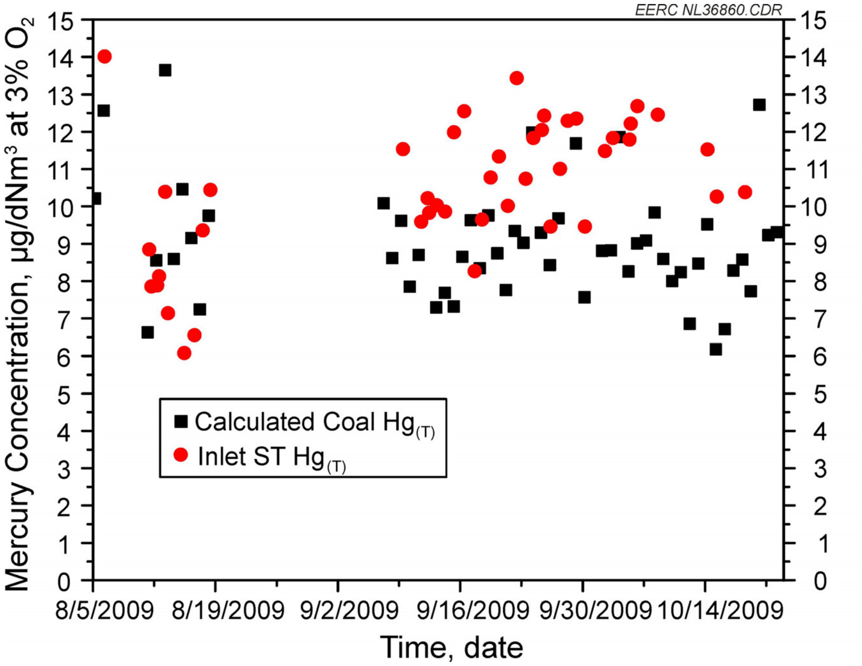


Figure 7. Comparison of the inlet mercury flue gas concentrations based on ST data and as calculated from the mercury in coal.

Table 6 compares the average measured ST mercury concentrations to the average calculated coal flue gas mercury concentrations on a monthly basis. The results show that the ST mercury concentrations are more variable than the calculated coal flue gas mercury concentrations. This is somewhat expected because the ST measurements are only 1 hr in duration and are not always performed at the same time each day. The daily coal values represent a 12-hr sample collected from the coal belt. The table shows a slight increase in the relative difference between the two data sets on a month-to-month basis, but the overall average relative difference remained <10%.

Table 6. Monthly Comparison of ST and Uncontrolled Flue Gas Mercury Data

Parameter	August	September	October	Average
Hg, µg/dNm^3, 3% O_2 (from ST measurements)	8.76	10.93	11.59	10.48
Hg, µg/dNm^3, 3% O_2 (from coal uncontrolled)	9.67	8.94	8.74	9.01
Relative Difference, %	4.94	10.01	14.01	7.54

TEST PLAN

To address the project objectives, the EERC assisted TransAlta in developing a test plan using various SEA and sorbent combinations to obtain a target mercury removal rate of ≥ 80%. RLP SF10 was injected into the furnace at the midpoint of the burners, and RLP-formulated sorbents were injected upstream of the Lodge ESP inlet. Norit Americas sorbents were also injected upstream of the Lodge ESP inlet. Parametric and extended tests were performed on the entire unit in order to accurately assess the mercury removal across the scrubber. This provided accurate inlet-to-stack mercury removals and allowed for a better evaluation of plant impacts.

A detailed SSTP was developed through discussions with TransAlta and the plant, detailing all aspects of the test program, and is available as a separate document (3). As part of the SSTP, a test matrix was developed to evaluate the injection of sorbents and a SEA provided by RLP Energy, which was selected to be the best-performing option for this plant. The test plan consisted of baseline, parametric, and extended test periods as well as additional alternative SEA parametric and extended tests.

The test schedule is shown in Table 7. Parametric testing days were approximately 12 hr in length. Extended tests consisted of continuous injection throughout the test period. Many different additive and sorbent combinations were evaluated throughout the test program.

Parametric testing consisted of multiple injection rates (amounts) for each test material to establish a mercury removal curve. A mercury removal curve allows the data to be extrapolated beyond the last injection rate tested and also provides estimated mercury removals for any injection curve. This allows for approximate SEA–sorbent injection rates to be ascertained at mercury removal rates of interest, such as 70% and 80%.

During the extended tests, specified injection rates were tested, which targeted 60%, 70%, 80%, and 90% mercury removals. The injection rates were determined based on the parametric mercury removal curves.

Table 7. Test Schedule

Dates	Description
August 5–6	Baseline
August 7–10	Unit off-line
August 10–11	Baseline
August 11–18	Parametric testing
August 11	DARCO Hg-LH
August 12	DARCO Hg-CC
August 13	SF10
August 14	
August 15	SF10–SB24
August 16	SF10–SB26
August 17	SF10–SB21
August 18	SF10–SB17
September 9–12	Baseline
September 12–16	Extended Test 1
September 17–22	Extended Test 2
September 24–27	Extended Test 3
September 27	Extended Test 1, additional test
September 27–29	Extended Test 2, additional test
September 29–30	Extended Test 4
October 1	Recovery day
October 2	DARCO Hg-LH, high rates
October 3	DARCO Hg-CC, high rates
October 4	Recovery day
October 5–6	Baseline/recovery
October 7–22	Alternative SEA testing
October 7	SC1–SB24
October 8	SC1–SB24
October 9–10	Alternative SEA skid shakedown
October 11	SC3–SB24
October 12–13	SF10–SB24
October 14–15	SF10–SB24 with TIFI injection
October 18	SC1–SB24 extended test
October 19	SC1–SB24
October 21	SC6–SB24
October 22	SF10–SB24

Flue Gas Sampling

To determine baseline emissions and technology effectiveness, mercury percent removals were calculated using mercury-in-coal concentrations along with ST and CMM measurements at the Koppers inlet, Lodge inlet, ID fan outlet, and stack-sampling locations. The error in the flue gas mercury measurements is estimated to be approximately ±5%.

Continuous Mercury Monitors

Two different brands of CMMs were used during the test period. The plant CMM and one EERC CMM were Tekran Series 3300 systems; they utilize a cold-vapor atomic fluorescent spectrometry (CVAFS) analyzer in conjunction with a dry conversion system and sampling probe to measure speciated mercury in a flue gas stream. The sample gas is pulled through a stack- or duct-mounted, high-flow-rate inertial probe to minimize mercury measurement artifacts due to filtering. The sample is then diluted and transported through a heated line to a conditioning module. The diluted sample is split into two streams. In the first stream, a thermal conditioner unit reduces all of the mercury forms present in the sample to elemental mercury. Recombination is avoided by the quantitative removal of HCl and other gases by a patented thermal conditioner/scrubber system. The second pathway removes ionic (water-soluble) mercury, leaving only the elemental mercury to pass through to the converter. This stream is then subjected to additional conditioning to remove acid gases and excess humidity from the sample. Ionic mercury is determined by difference. This conversion unit has the advantage of not using chemical reagents or solid sorbents.

The probe is capable of performing automated filter blowback, multipoint calibrations, and standard additions of elemental mercury into the sample matrix. Probe temperatures, flow rates, and pressures are monitored and telemetered to the system controller via a datacom link.

The two conditioned streams are analyzed using a Tekran Model 2537A mercury vapor analyzer that uses gold preconcentration combined with atomic fluorescence detection. The advertised minimum detection limit for the analyzer is $<0.05\ \mu g/m^3$. A source of compressed mercury-free argon is required for operation of the instrument. The Tekran instrument traps the Hg vapor from the conditioned sample onto a cartridge containing an ultrapure gold sorbent. The amalgamated Hg is then thermally desorbed and detected using atomic fluorescence spectrometry. A dual-cartridge design allows alternate sampling and desorption, resulting in continuous measurement of the sample stream. The Model 2537A allows two methods of calibration: manual injection or automatic permeation source. Permeation source calibration was used as the primary calibration to calibrate the instrument daily. Manual injection calibration on both cartridges was performed for verification. The Tekran instrument can measure either $Hg_{(T)}$ or Hg^0, with one analysis point being obtained approximately every 2.5 minutes. The system is designed only to measure the mercury concentration in the vapor phase, so the contribution of particulate-bound mercury was not measured. The plant Tekran CMM was located in the stack, and the EERC Tekran CMM was located at the south side ID fan outlet. CMM data can be found in Appendix B.

The second EERC CMM system was a Thermo Scientific Mercury Freedom System^{TM}. The Thermo Scientific Mercury Freedom System consists of a mercury analyzer, mercury calibrator, zero air supply, stack probe and inertial filter, converter, and probe control system. The mercury analyzer is a CVAFs design that provides continuous sample measurement, with no additional gases or preconcentration required and virtually no interference from SO_2. Detection limits down to 1.0 ng/m^3 allow high sample dilution (100:1), minimizing moisture, heat, and interfering pollutants.

The extraction probe uses an inertial filter to separate a particulate from the gas-phase sample, minimizing reactions of mercury and other species with fly ash. All components that are exposed to sample gas are glass-coated to prevent reactions with mercury. The probe incorporates a dilution assembly and calibration gas that can be introduced either upstream or downstream of the inertial filter. A high-temperature module converts all vapor-phase species of mercury to Hg^0 for analysis. The Hg^0 calibrator is available to provide output range from 0.1 to 300 μg/m^3.

The mercury analyzer is designed for use with a dilution probe. The zero air supply provides dry, mercury-free dilution air to the probe, zero gas for analyzer calibrations, and air to the mercury calibrator.

The probe control system allows for mercury spiking and autodilution, as well as automating the processes. This system is able to provide simultaneous total, elemental, and oxidized (by difference) mercury data at intervals ranging from 30 s to 3 min. For this test program, the analyzer collected data every 1 min.

Sorbent Trap Sampling

A ST method (similar to EPA Method 30B) was used to evaluate the comparative accuracy of the CMM results. The ST samples were collected with single, two-stage traps and were recovered and analyzed for mercury on-site in the EERC mobile laboratory; mercury analysis was performed using an OhioLumex mercury analyzer that is based on a thermal decomposition procedure validated by EPA followed by detection using AAS. Results of the ST sampling are shown in Appendix C. Appendix D details sample calculations for the ST samples as well as other relevant calculations used throughout the project.

The quality assurance/quality control (QA/QC) program for analyzing the STs consisted of an initial analysis of blanks, calibration, and check standards followed by periodic checks on performance. Detailed performance records are maintained that define the quality of the data generated. The EERC chemist who performed the analysis was well trained and understands the procedures for using the OhioLumex both in the laboratory and in the field. The following outlines the calibration standards and QA/QC procedures that were followed:

- Calibration standards were prepared from National Institute of Standards and Technology (NIST)-traceable standards to span the range of sample values; the generated calibration curve was required to have an r^2 value greater than 0.99. If these requirements were not met, then the instrument was recalibrated with remade standards as necessary.

- A QC standard was made from a NIST-traceable standard from a different lot than the calibration standards and analyzed to compare to the calibration curve. This standard was required to be within ±10% of its expected value. If it was not, then either the QC standard was remade and analyzed again or the instrument calibration was rechecked. It should be noted that, for this project, all QC standards fell within the ±10% specification.

- Analyzer calibrations are usually very stable and may be used for several days; the EERC either made or verified the calibration curve each day. QC checks at the high and low calibration points on the curve were done a minimum of twice a day (once after generating/verifying the calibration curve and once near the end of the day).

- A QA check at a concentration close to that being analyzed was made for every ten samples or twice a day, whichever was greater. If these values were within ±10% of the known standard, the calibration was still valid.

- If a calibration had to be repeated after the samples were analyzed, the data for all the samples analyzed since the last valid calibration were recalculated, based on the new calibration curve. Because the samples had been completely desorbed, it was not possible to run them again; therefore, a recalculation was done using computational processes based on the manufacturer's instructions for calculation of data. It should be noted that, for this project, all check standards fell within the ±10% specification.

- All documentation was recorded in project notebooks and/or on the computer. Data records stored on a computer were maintained and backed up. Following testing, all data sheets and log books were initialed by the person completing the analysis and reviewed for completeness and accuracy. Any changes or corrections that needed to be made were initialed, dated, and noted.

Trace Metal and Particulate Sampling

Trace metal emissions at the Lodge inlet and the stack were determined using EPA M29, which was developed for measuring the solid particulate and gaseous emissions of mercury and 16 other trace elements (antimony, arsenic, barium, beryllium, cadmium, chromium, cobalt, copper, lead, manganese, nickel, phosphorus, selenium, silver, thallium, and zinc). The stack sampling was conducted in the southwest port of Unit 2. A probe with a length of 10 ft was used for the M29 sampling. During the test, the probe was inserted to a depth of approximately 8 ft. No traversing was performed during the M29 testing, and the entire test was conducted in the same port. The test duration was 2 hr for each of the tests.

A schematic of the EPA M29 sampling train is presented in Figure 8. The EPA M29 sampling train consists of seven impingers. Following an optional moisture knockout impinger, gaseous mercury species are collected in two pairs of impingers connected in series containing

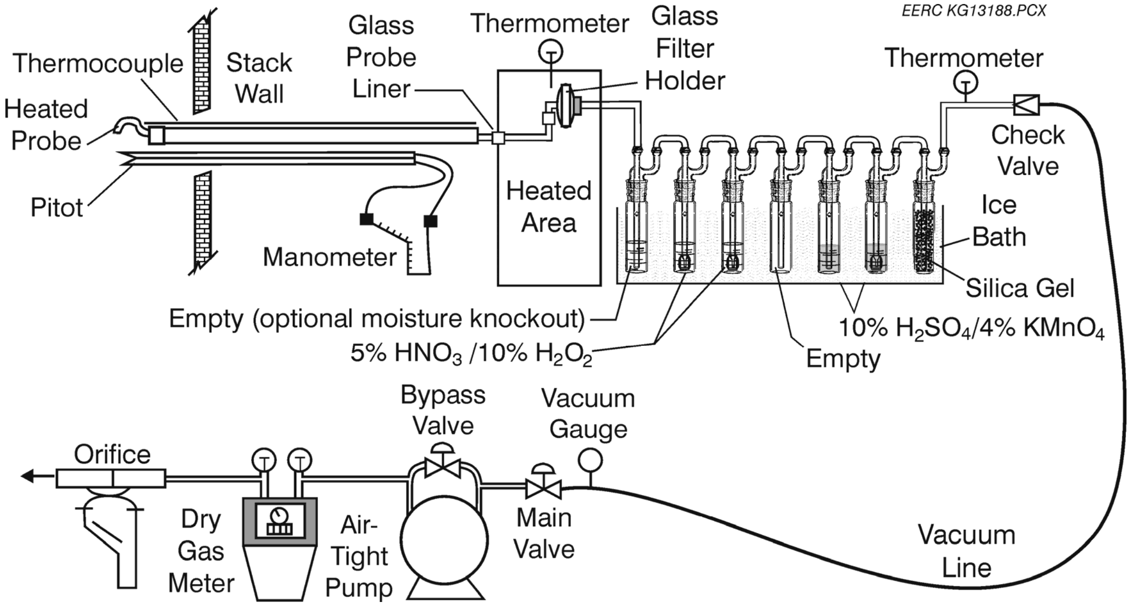


Figure 8. A schematic of the EPA Method 29 sampling train.

different absorption solutions. A portion of the gaseous mercury is captured in the first pair of impingers containing aqueous solutions of 5% nitric acid (HNO_3) and 10% hydrogen peroxide (H_2O_2), while the remainder is captured in a second pair of impingers containing aqueous solutions of 4% potassium permanganate ($KMnO_4$) and 10% sulfuric acid (H_2SO_4). An empty impinger is located between the two sets of impingers to reduce the potential for blowback of $KMnO_4$ into the second HNO_3/H_2O_2 impinger during leak checks. The last impinger in both sampling trains contains silica gel to prevent contamination and entrap moisture that may otherwise travel downstream and damage the dry gas meter and pump. Data from M29 and M5 samples are provided in Appendix E.

Particulate sampling was determined using EPA M5 extractive sampling. This method is a partial requirement for EPA M29 and so was adapted. M29 requires a quartz filter be used before the sampling train to capture particulates before the gas stream reaches the impinger solutions. By weighing the filter before and after the M29 sampling, the requirements for M5 are met.

Halogen Sampling

Total halogen emissions at the Lodge inlet and the stack were determined using EPA M26a. This method utilizes a sampling train similar to the one used for EPA M29. Samples were withdrawn from the flue gas stream isokinetically through a probe/filter system, maintained at the flue gas temperature, and followed by a series of impinger solutions in an ice bath. A quartz filter was used in the front half of the sampling train to capture any particulate matter in the gas stream. Hydrogen halides were collected in impingers containing a chilled aqueous sulfuric acid solution. Halogens were collected in subsequent impingers containing aqueous sodium hydroxide solution. The stack sampling was conducted in the southwest port of Unit 2. The probe length was 10 ft with a sampling depth of approximately 8 ft. No traversing or port moving was performed during the M26a test. The test length was 1 hr in duration for each of the tests. Samples were recovered and sent to the lab for analysis. Data from M26a samples are provided in Appendix E.

Plant Data

Throughout the entire test program, plant operational data were recorded and are shown in Appendix F. The data were obtained to determine if any significant balance-of-plant (BOP) impacts occurred as a result of the mercury control project. The data included unit load, coal flow, flue gas temperatures, air heater (AH) differential pressure, ESP data, NO_x, SO_2, O_2 (various locations), and opacity.

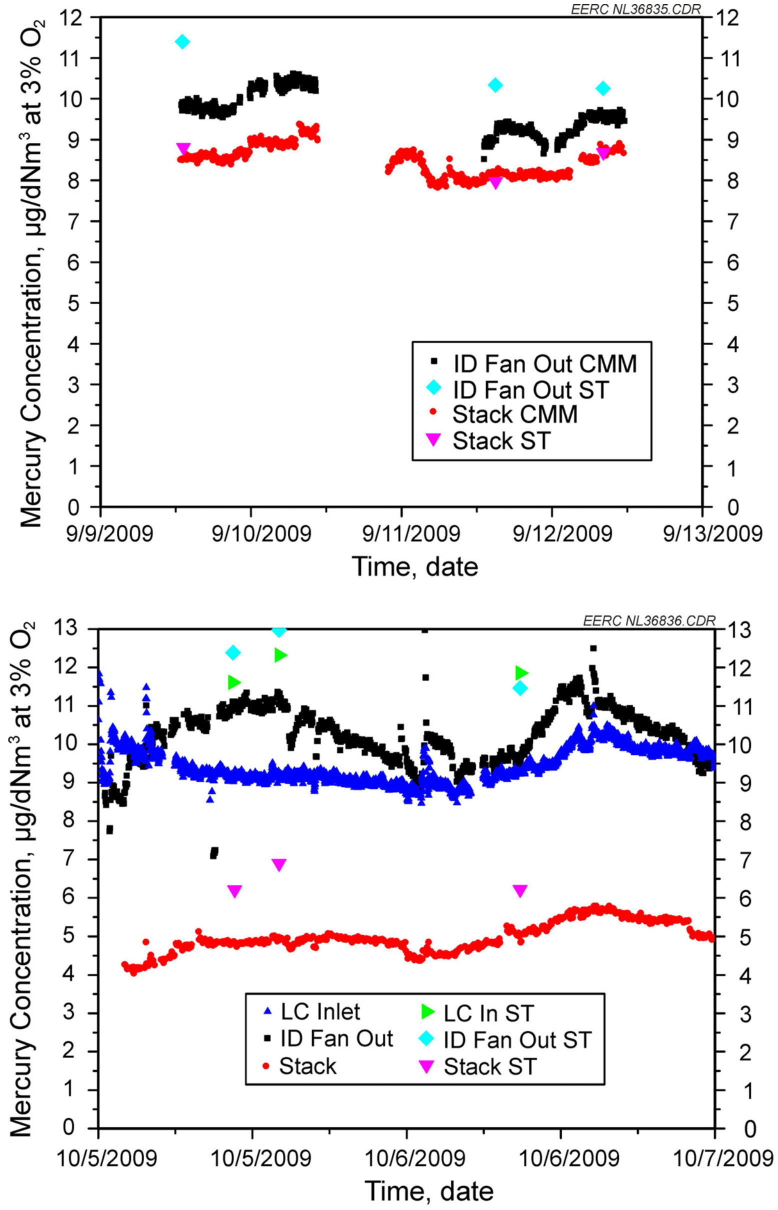
TEST RESULTS

Baseline Tests

Baseline sampling and measurements were taken at three periods during the test. The first baseline test period was August 5–6 and August 10–11, 2009, prior to parametric testing. The second baseline test period was September 9–12, 2009, prior to the extended tests. The third baseline/recovery period was October 5–6, 2009, just after the extended test period and before the alternative SEA tests.

During the August baseline test period, the plant went off-line and switched coal supplies, which resulted in the baseline data being not representative of the test conditions. Baseline sampling consisted of ST measurements at the Koppers inlet, Lodge inlet, ID fan outlet, and stack. In addition, CMMs were operated at the Lodge inlet, ID fan outlet, and stack. Total and elemental vapor-phase mercury concentrations measured with the CMMs at the Lodge inlet, ID fan outlet, and stack are compared along with the corresponding ST measurements in Figures 9a and b for the September and October baseline test periods, respectively. The CMM concentrations in Figure 9a show that the mercury concentration remained consistent during the baseline test period. During the September baseline, inlet-to-stack ST measurements yielded an average mercury removal of 18.5%. The CMM data at the ID fan outlet indicated that 70.2% of the mercury was present in the elemental form. At the stack, the CMM indicated that 97.6% of the mercury was in the elemental form. The ID fan outlet and stack average CMM concentrations were 9.67 $\mu g/dNm^3$ at 3% O_2 and 8.44 $\mu g/dNm^3$ at 3% O_2. The ST and CMM measurements correlated well and exhibited a relative difference of $\leq$ 10%.

The October baseline/recovery days plotted in Figure 9b show that the system was recovering from the tests that were conducted prior to the baseline test period. The $Hg_{(T)}$ CMM data at the ID fan outlet agreed well with the previous baseline data, but the Hg^0 data were much lower than the data in Figure 9a. This shows that the unit was still recovering from the previous test periods and also explains why the stack emissions were lower than in Figure 9a. The additional oxidized mercury was removed by the scrubber, which resulted in the lower stack emissions.



a)

b)

Figure 9. Figure 9a (top) displays the September baseline CMM data; Figure 9b (bottom) displays the October baseline CMM data.

Parametric Tests

Following the August baseline test period, parametric tests were performed to determine the sorbent injection rates necessary to obtain ≥ 80% mercury removal. Each parametric test was performed long enough for the CMMs to reach an apparent steady state, typically for durations of 0.5 to 4 hr. Injections were started at relatively low rates and then systematically increased to higher injection rates in order to minimize potential memory effects from the higher injection rates. One technology was tested a day to allow the unit to recover overnight and return to baseline conditions. During many of the parametric tests, ST measurements were made to compare the ST values to the CMM values.

Norit Americas Sorbents

Two Norit Americas sorbents, DARCO Hg-LH and DARCO Hg-CC, were parametrically tested to evaluate their mercury removal effectiveness. DARCO Hg-LH is a brominated AC that has been shown to increase mercury removal for low-halogen coals. DARCO Hg-CC is a treated AC that is reported to have concrete-compatible characteristics.

Figure 10 displays the percent mercury removals during the injection of DARCO Hg-LH. The first injection rate of 75 lb/hr yielded mercury removals of 24.84% and 33.81% at the ID fan outlet and stack, respectively. The mercury removals increased until a maximum stack mercury removal of 81.79% at an injection rate of 520 lb/hr. Higher injection rates were not tested

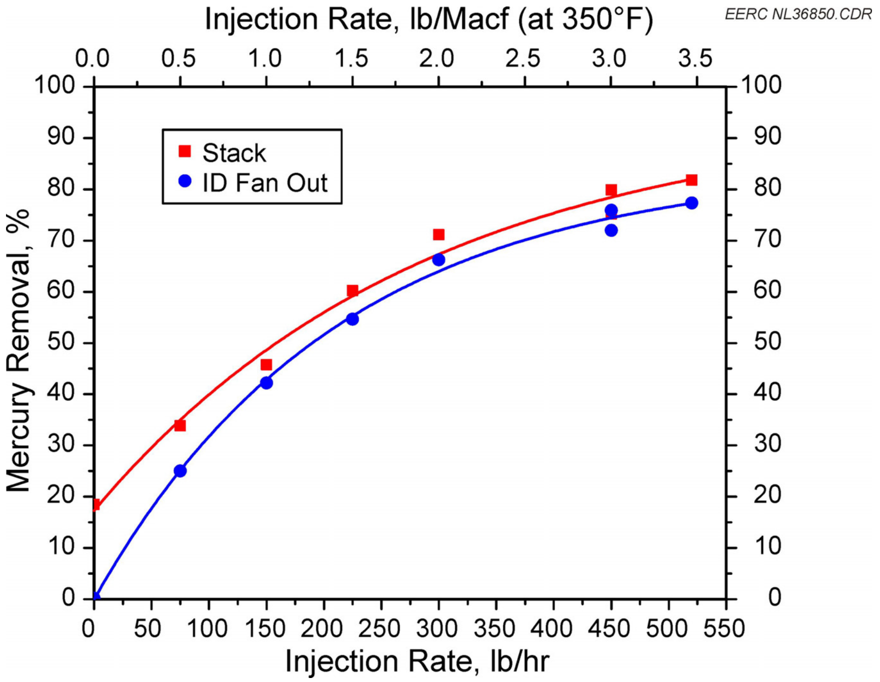


Figure 10. ID fan outlet and stack percent mercury removals as a function of DARCO Hg-LH injection rates. Injection rates are for the entire unit.

because they were not economically feasible. Most of the mercury removal occurred in the Lodge ESPs, with approximately an additional 5% mercury removal in the scrubber.

The next Norit Americas sorbent tested was DARCO Hg-CC; Figure 11 displays the percent mercury removal curve for this sorbent. The shape of the curve is slightly different than a normal injection curve, such as seen in Figure 10; this is likely due to memory effects from the previous day of testing. Based on the shape of the curve, the mercury removal for the baseline and first two injection rates is biased high. Neither the Lodge ESPs nor the stack had completely recovered overnight because mercury measurements taken at both the ID fan outlet and stack were biased high for the first two data points. This phenomenon is not seen in most plants, but was shown at this plant because of the unique configuration and sorbent injection location. As a result of the injection location, the sorbent-to-ash ratio is much higher than that typically observed because the Koppers ESPs remove the majority of the fly ash. In Figure 12, the first two injection data points have been removed, and the average baseline removals were used to generate a new mercury removal curve. The curve shape now has a normal appearance, with a smooth increase that begins to plateau at the higher injection rates.

RLP Energy SEAs and Sorbents

In addition to the Norit Americas sorbents, several front- and back-end mercury removal technologies provided by RLP Energy were parametrically tested to determine their mercury

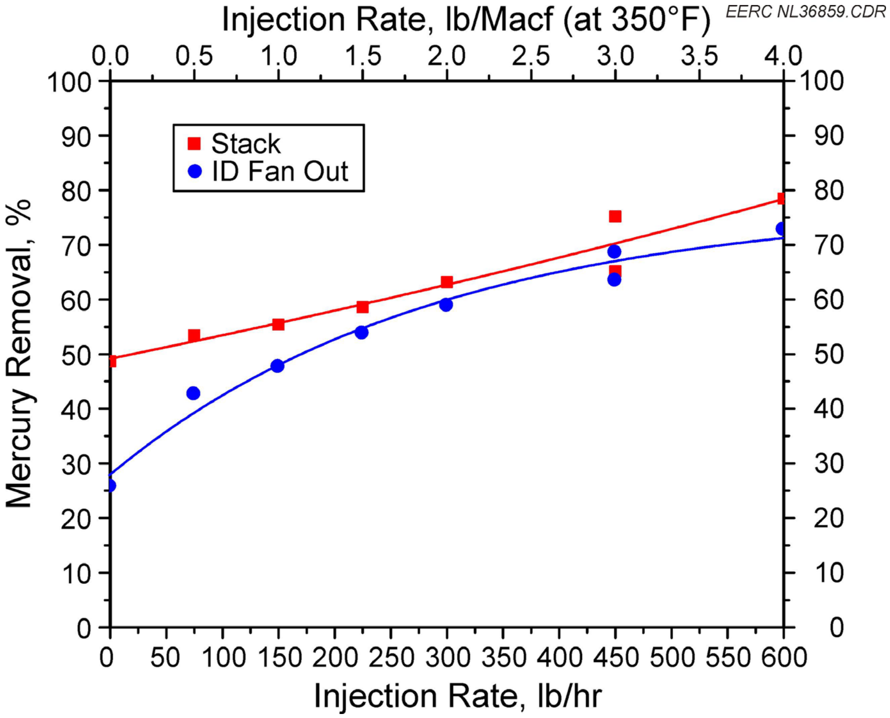


Figure 11. ID fan outlet and stack percent mercury removals as a function of DARCO Hg-CC injection rates.

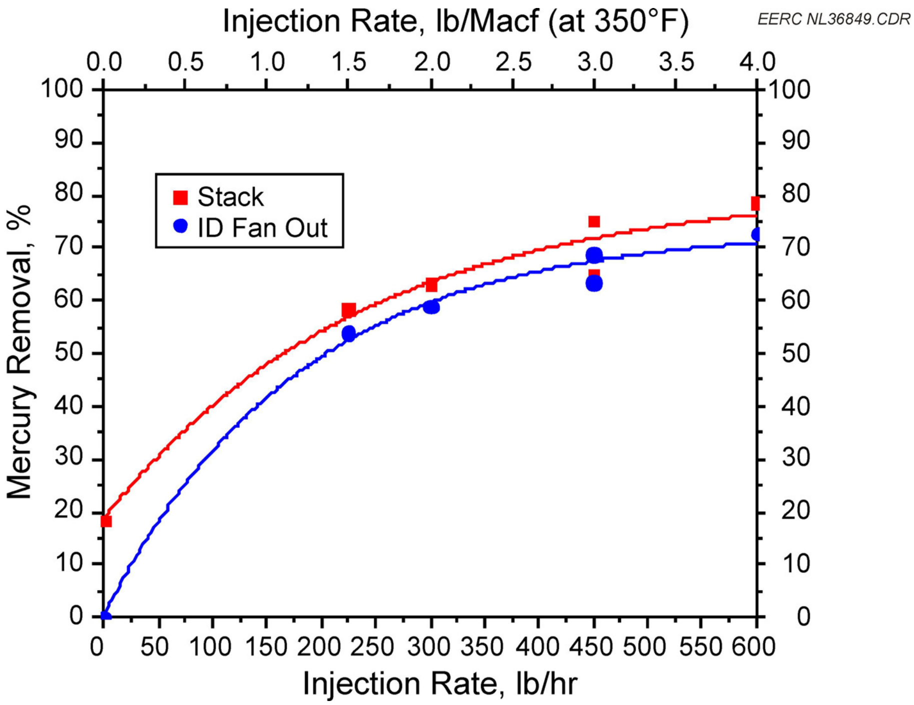


Figure 12. DARCO Hg-CC mercury percent removal curves as a function of injection rate. The first two data points have been omitted, and the average baseline values were used.

removal effectiveness. Both carbon-based and non-carbon-based sorbents were tested in conjunction with an SEA, SF10. The furnace SEA is added in conjunction with the back-end sorbent to provide a synergistic effect between the two materials, which results in an increase in the amount of mercury subsequently captured in the APCDs of the test unit.

SF10

SF10 was parametrically tested by itself to determine its mercury removal effectiveness. SF10 is a furnace SEA which is commercially available from RLP as part of a front- and back-end technology combination. SF10 can be combined with a variety of back-end sorbents to meet the specific needs of a given unit. The percent mercury removals for SF10 injection are presented in Figure 13. The SF10 mercury removal curve increases from baseline and reaches a maximum stack mercury removal of 68.0% at a relatively high SF10 injection rate of 102 lb/hr. Based on the ID fan outlet and stack mercury removal curves, approximately 50% of the mercury removal occurs across the ESPs, with the remaining 50% occurring across the scrubber. Based on the injection data, a mercury removal of approximately 30% occurs across the scrubber, which is higher than the baseline mercury removal of 18.5%. This indicates that there is the possibility for increased mercury concentrations in the scrubber and scrubber by-products when SF10 alone is injected for mercury capture compared to baseline conditions.

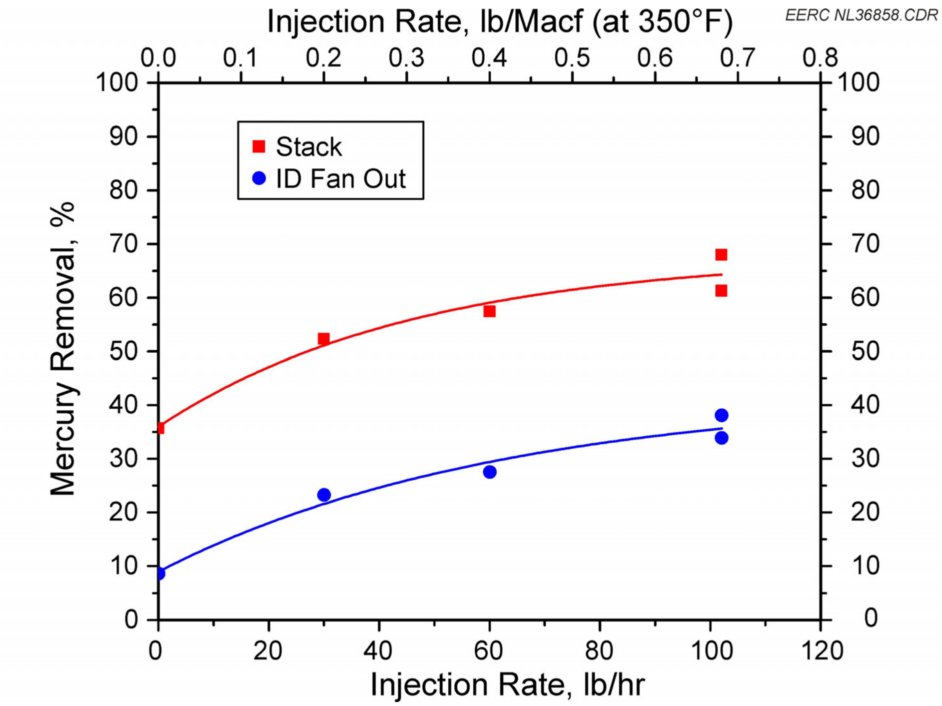


Figure 13. ID fan outlet and stack percent mercury removals as a function of SF10 injection rates. Injection rates are for the entire unit.

RLP Energy SF10 and Carbon-Based Sorbents

A number of RLP carbon-based sorbents were parametrically tested along with SF10 to determine their mercury removal capabilities, including SB21 and SB24. The first technology combination tested was the SF10–SB24 technology. As seen in Figure 14, the SF10–SB24 mercury removal curve increases sharply and does not begin to plateau until the mercury removals are in the 90% range. The first injection rate of 30 lb/hr SF10 plus 75 lb/hr SB24 achieved a stack mercury removal of 72.68%. A maximum mercury removal of 91.73% was obtained at SF10 plus SB24 injection rates of 90 and 450 lb/hr, respectively. At SF10 plus SB24 injection rates of 45 and 150 lb/hr, a mercury removal of 83.27% was obtained.

When the SF10 injection rate alone was increased, there was no significant improvement in mercury removal, as shown in Figure 14; at the SB24 injection rate of 150 lb/hr, three SF10 injection rates were tested. Most of the mercury was removed in the Lodge ESPs, which is similar to the Norit Americas sorbents. Since most of the mercury is removed in the ESPs, the scrubber mercury concentration is expected to be at or below baseline concentration levels.

The SF10–SB21 technology was the next carbon-based technology tested. Figure 15 displays the percent mercury removal results for SF10–SB21. A mercury removal of 80.66% was obtained at SF10 plus SB21 injection rates of 45 and 225 lb/hr. The mercury removal curve began to plateau at SF10 plus SB21 injection rates of 60 and 450 lb/hr, respectively. A maximum

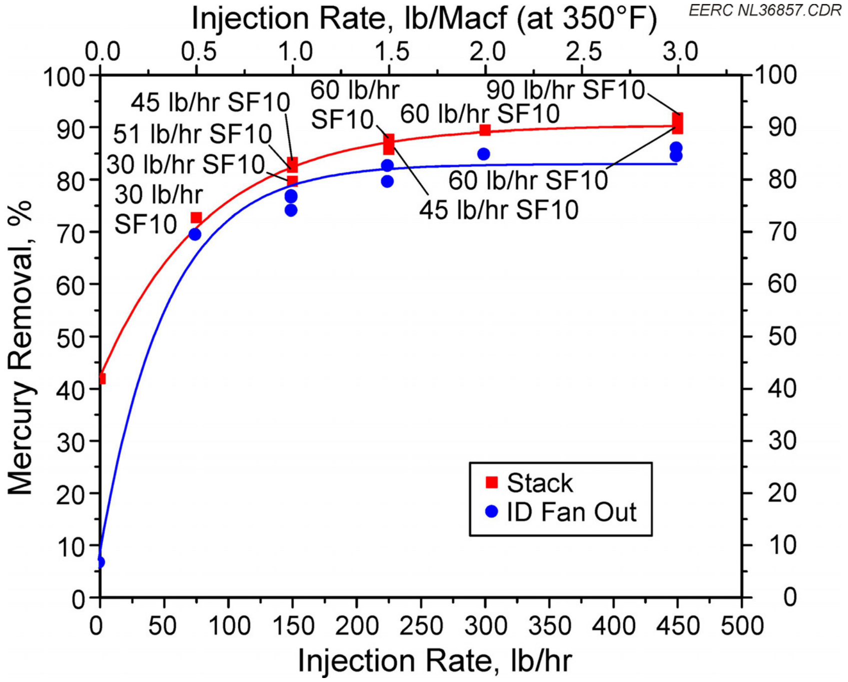


Figure 14. ID fan outlet and stack percent mercury removals as a function of SF10–SB24 injection rates. Injection rates are for the entire unit.

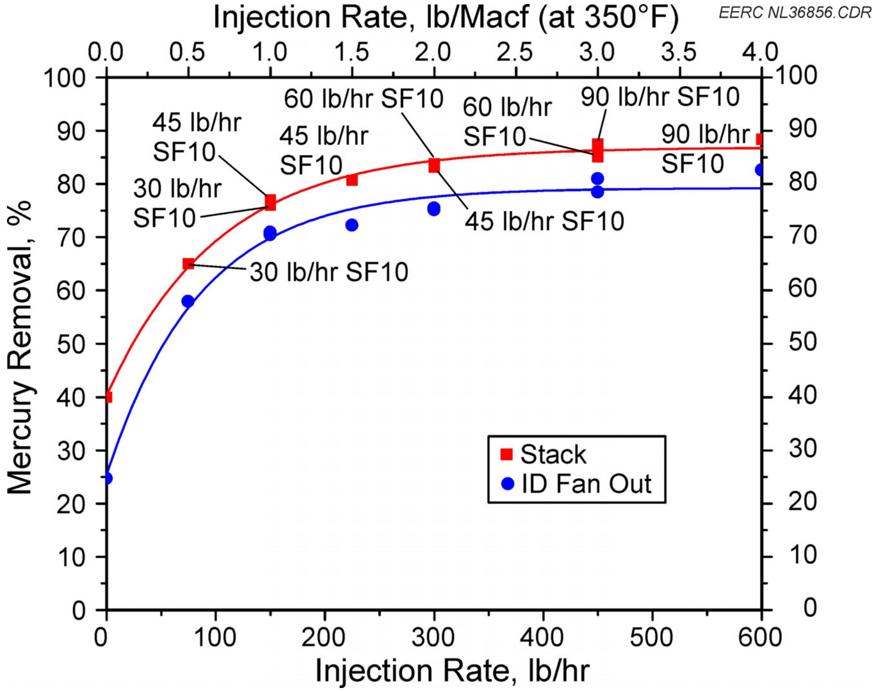


Figure 15. ID fan outlet and stack percent mercury removals as a function of SF10–SB21 injection rates.

mercury removal of 88.36% was obtained at SF10 plus SB21 injection rates of 90 and 600 lb/hr, respectively. The performance of the SF10–SB21 technology was not as good as SF10–SB24, but the technology did perform better than DARCO Hg-LH and DARCO Hg-CC.

RLP Energy Non-Carbon-Based Sorbents

In addition to the carbon-based sorbents, two RLP Energy non-carbon-based sorbents, SB17 and SB26, were parametrically tested to determine their mercury removal effectiveness. Non-carbon-based sorbents were tested because of their potential concrete-compatible characteristics. Figure 16 displays the percent mercury removal results for the SF10–SB26 technology. The high initial removals indicate that the unit had not completely recovered from the previous day. The mercury removal curve at the ID fan outlet exhibits a slight increase and then plateaus after the first injection rate. The stack mercury removal curve increases slowly with increasing injection rates and reaches a maximum mercury removal of 82.36% at SF10 and SB26 injection rates of 90 and 450 lb/hr, respectively. With this technology, more of the mercury is removed in the scrubber than with the previous technologies. The previous technologies tested indicated approximately a 5% increase in mercury removal across the scrubber. The highest SF10–SB26 injection rate shows approximately a 20% increase in mercury removal from the ID fan outlet to the stack.

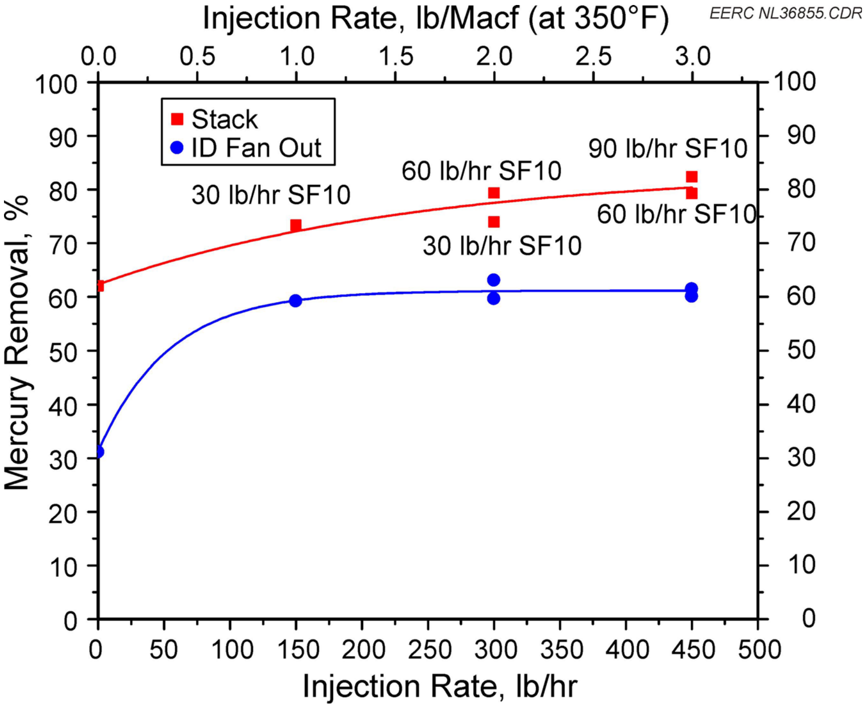


Figure 16. ID fan outlet and stack percent mercury removals as a function of SF10–SB26 injection rates. Injection rates are for the entire unit.

The last parametric test was with the SF10–SB17 technology. Figure 17 displays the mercury removal results for the SF10–SB17 parametric tests. The ID fan outlet mercury removal curve is very flat and plateaus after the first injection rate. As seen in Figure 16, a higher percentage of mercury, up to approximately 20%–25%, was removed across the scrubber. A maximum mercury removal of 80.82% was obtained at SF10 plus SB17 injection rates of 90 and 450 lb/hr, respectively. The data from Figures 16 and 17 suggest that while the sorbents were not as effective in capturing the mercury they did facilitate oxidation which resulted in improved mercury capture within the scrubber.

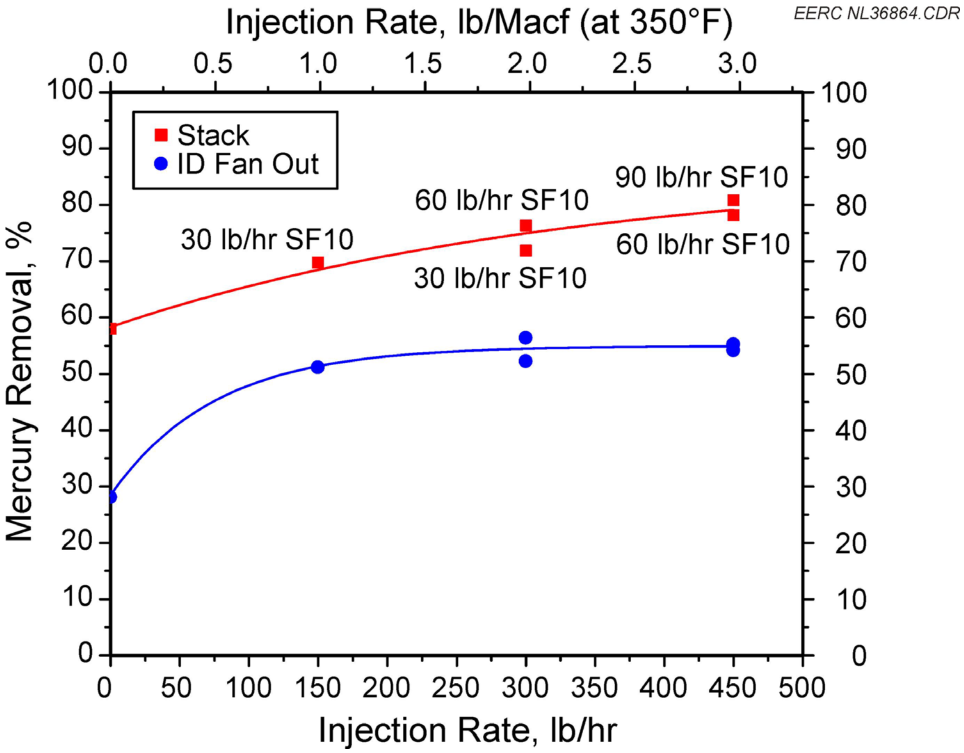


Figure 17. ID fan outlet and stack percent mercury removals as a function of SF10–SB17 injection rates.

Extended Tests

In the initial test plan, one 21-day extended test was scheduled. Based on discussions between TransAlta, the plant, and the EERC, the extended test matrix was revised. Rather than one 21-day extended test, four extended tests targeting 60%, 70%, 80%, and 90% mercury removal were scheduled. Following the extended tests, 2 days were spent testing high injection rates of DARCO Hg-LH and DARCO Hg-CC. These data were incorporated into the parametric test results for these two sorbents and are shown in Figures 10 and 12. Each extended test was scheduled to last approximately 5 days in length and consist of continuous 24 hours a day of sorbent injection for the duration of the test period. SF10–SB24 was the technology chosen for the extended tests because of its strong performance during the parametric test period.

The first extended test (ET1) was 5 days in duration and targeted a 60% mercury removal using SF10–SB24 at injection rates of 20 and 50 lb/hr, respectively. Figure 18 plots the percent mercury removal using both the ST and coal inlet values along with the plant load. The figure shows that there is a slight difference between the coal and ST inlet values. The stack ST and CMM measurements show excellent agreement, and the removals are consistent regardless of what stack value is used to determine the percent mercury removal. The average ST inlet-to-stack CMM outlet mercury removal was 72.4%.

The load remained constant throughout the test period except for one period when the load decreased down to approximately 500 MW for approximately 4 hr. The load was dropped in order to clean slag from the boiler walls. During this time, the mercury removals increased to

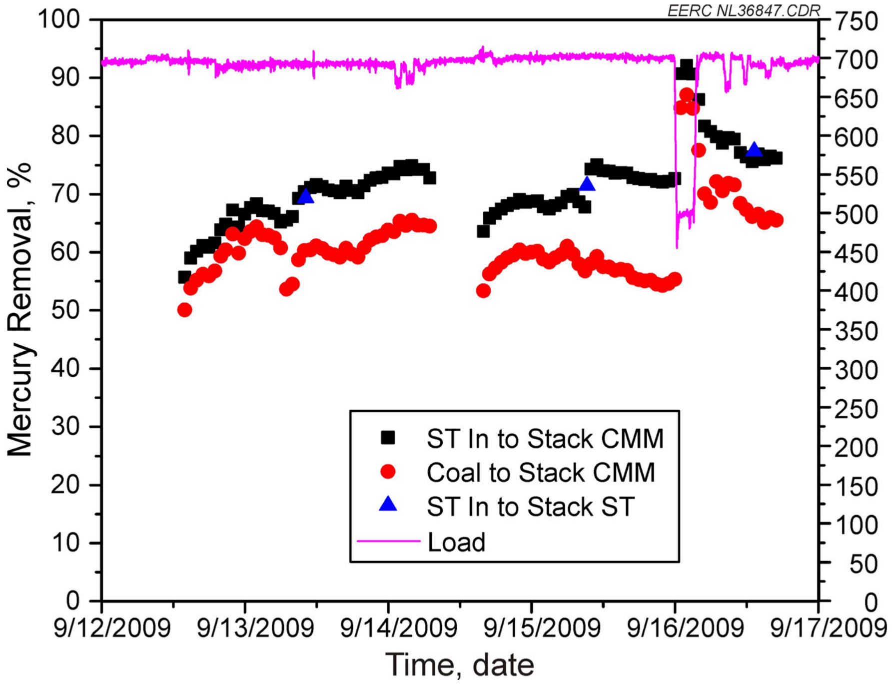


Figure 18. Coal-to-stack and ST inlet-to-stack mercury removals during ET1. SF10 and SB24 injection rates were 20 and 50 lb/hr, respectively. Injection rates are for the entire unit.

over 90%. This effect occurred because the injection rate remained constant, but the flow through the unit decreased. Since the unit flow decreased, the lb/Macf of sorbent increased, which led to an increase in mercury removal. After the load returned to full load, the mercury removal reached steady-state conditions after approximately 5 hours. Mercury percent removals during low load conditions were omitted from this and subsequent extended tests when calculating mercury removals because of the bias introduced by these conditions.

For ET2, the SF10 and SB24 injection rates were increased to 25 and 100 lb/hr, with a target mercury removal of >70%. Figure 19 displays the hourly percent mercury removal results for the duration of ET2. The coal and ST inlet data agree well for this test period, with the removals typically within 5%. The stack and ST CMM data agree very well and are within 10% for the duration of the test. The average ST inlet-to-stack CMM outlet mercury removal was 87.5%, which is above the target mercury removal of >70%. The load remained fairly constant throughout the test period except for two incidents where it decreased to approximately 450 MW and 650 MW for a few hours. The load drop to 450 MW was to clean slag from the boiler walls.

ET3 was approximately 4 days in length and utilized SF10 and SB24 injection rates of 38 and 150 lb/hr, respectively. ET3 was slightly shorter in duration because of a plugged injection hose on the south side of the unit. The hose was cleared, and the test was started from the beginning. Figure 20 displays the hourly stack CMM mercury removal data plotted using both the coal and ST inlet values. The mercury removals were very similar when either the coal or

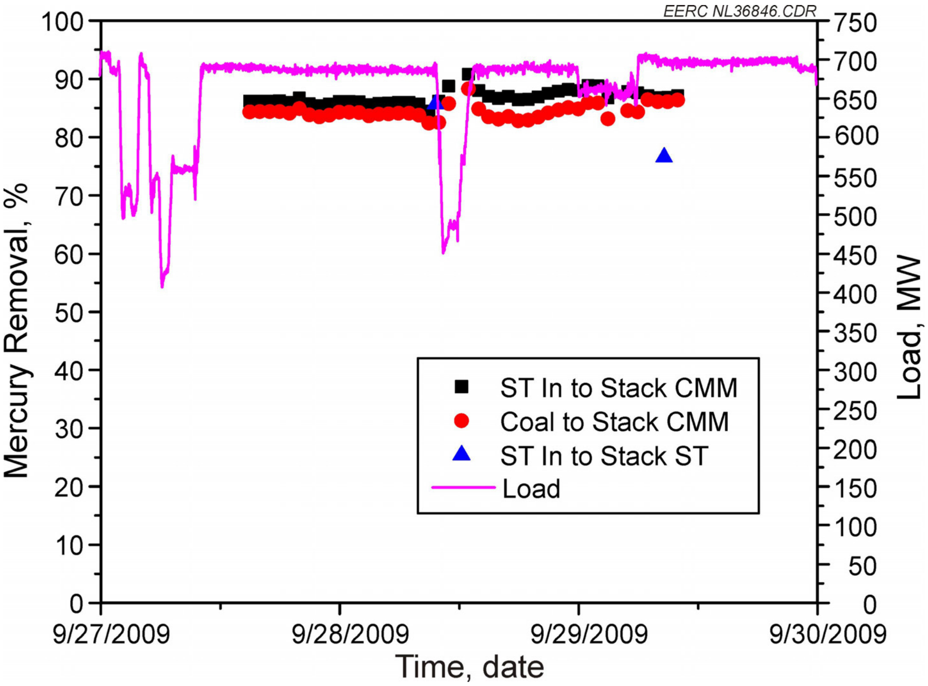


Figure 19. Coal-to-stack and ST inlet-to-stack mercury removals during ET2. SF10 and SB24 injection rates were 25 and 100 lb/hr, respectively. Injection rates are for the entire unit.

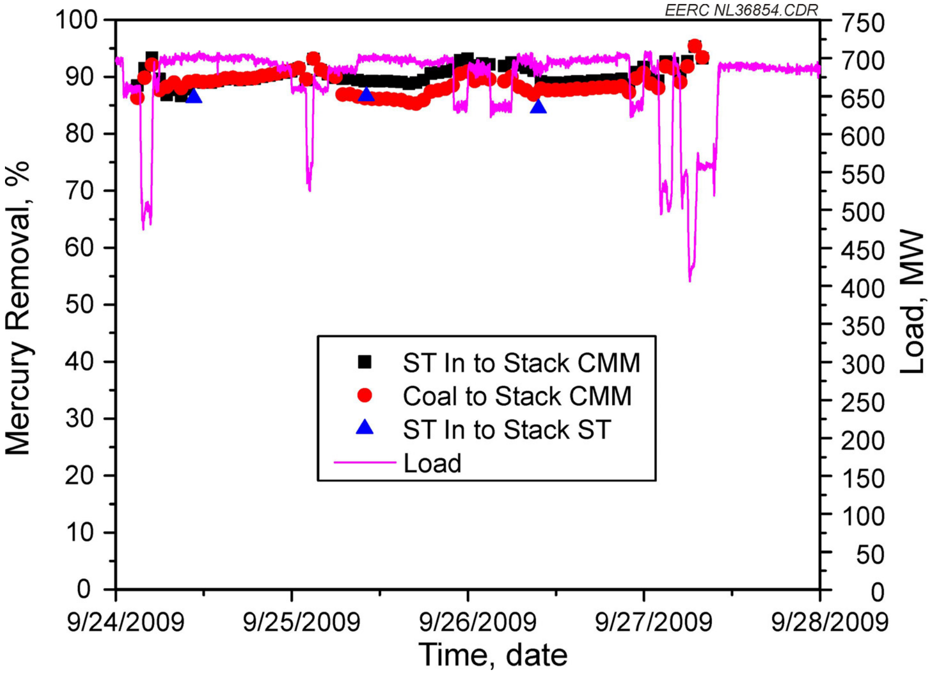


Figure 20. Coal-to-stack and ST inlet-to-stack mercury removals during ET3. SF10 and SB24 injection rates were 38 and 150 lb/hr, respectively. Injection rates are for the entire unit.

inlet ST value was used to determine the mercury removal, with <5% deviation for the duration of the test period. The ST inlet-to-ST outlet mercury removals agreed well with the CMM mercury removals and were within 5% for the duration of the test period. The load remained fairly stable throughout the test period, with only brief periods of the load decreasing to clean slag from the boiler walls. The average ST inlet-to-stack CMM outlet mercury removal was 90.4%, which is much higher than the target mercury removal of ≥ 80%.

The last extended test, ET4, involved injecting SF10–SB24 at high injection rates in order to determine the maximum mercury removal that is economically feasible for the unit. The test was shorter than the other extended tests and lasted for approximately a day. The SF10–SB24 injection rates tested were 60 and 225 lb/hr. Figure 21 displays the hourly stack CMM mercury removal data plotted using both the coal and ST inlet values. The removals based on the coal and ST inlet values show excellent agreement and are within 5% of each other. The inlet-to-outlet ST mercury removal also compares well with the CMM hourly removals. The average ST inlet-to-stack CMM outlet mercury removal was 92.4%. Even at these high injection rates, an increase in mercury removal was seen when the load was decreased to approximately 475 MW for a few hours.

Tables 8 and 9 display the ID fan outlet and stack average mercury removals for each of the extended tests, respectively. The mercury removals are calculated via three methods: ST inlet to CMM, coal to CMM, and ST inlet to ST outlet. Both tables show that there is only a slight difference between the three different calculation methods. The tables show that there is

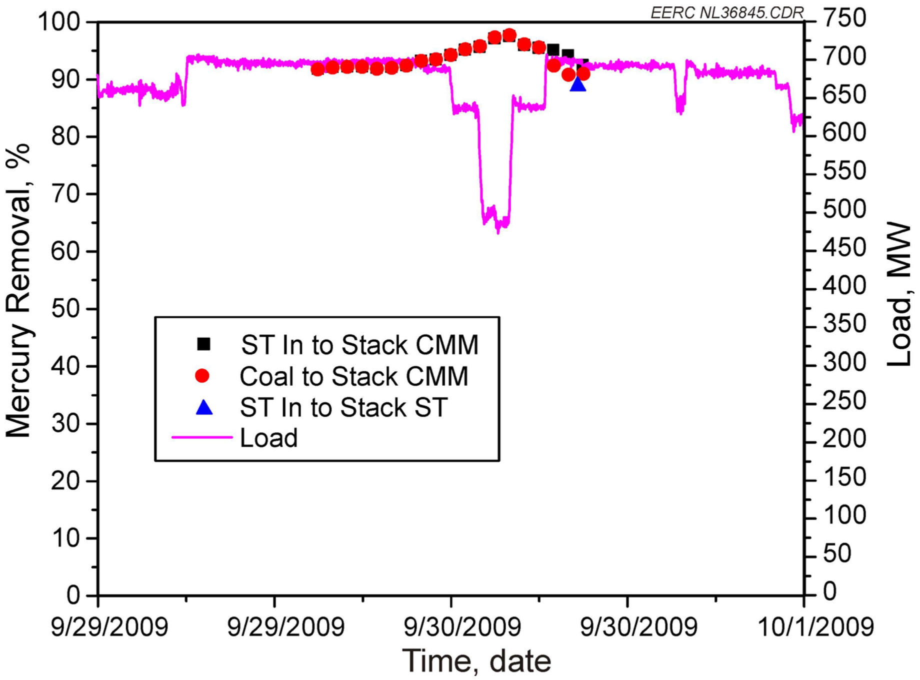


Figure 21. Coal-to-stack and ST inlet-to-stack mercury removals during ET4. SF10 and SB24 injection rates were 60 and 225 lb/hr, respectively. Injection rates are for the entire unit.

Table 8. Extended Test Mercury Removals at the ID Fan Outlet

	SF10, lb/hr	SB24, lb/hr	ST to CMM, %	Coal to CMM, %	ST Inlet to ID Fan Out ST, %	Average, %
ET1	20	50	59.3	53.8	57.7	56.9
ET2	25	100	69.0	64.3	67.8	67.0
ET3	38	150	77.6	74.0	73.7	75.1
ET4	60	225	79.6	80.0	80.4	80.0

Table 9. Extended Test Mercury Removals at the Stack

	SF10, lb/hr	SB24, lb/hr	ST to CMM, %	Coal to CMM, %	ST Inlet to Stack ST, %	Average, %
ET1	20	50	72.4	62.3	68.8	67.8
ET2	25	100	87.5	85.6	81.1	84.7
ET3	38	150	90.4	88.9	86.3	88.5
ET4	60	225	92.4	92.5	88.4	91.1

approximately a 10% increase in mercury removal across the scrubber during the extended tests. The parametric tests indicated only about a 5% increase in mercury removal across the scrubber. This shows that the scrubber requires additional time to reach steady-state mercury removal.

Figure 22 plots the data in Tables 8 and 9. The figure shows that the extended test data fit a smooth curve. Based on the stack mercury removal curve, 60% mercury removal can be obtained at SF10 and SB24 injection rates of 20 and 38 lb/hr, respectively. In order to obtain 70% mercury removal, the injection rates need to be increased to 22 and 54 lb/hr. Based on the stack mercury removal curve, 80% mercury removal can be obtained at SF10 and SB24 injection rates of 24 and 83 lb/hr. The extended test data show that 90% mercury removal can be achieved at injection rates of 52 and 178 lb/hr. These rates agree well with the parametric data and show that the parametric data provide useful estimates for extended tests.

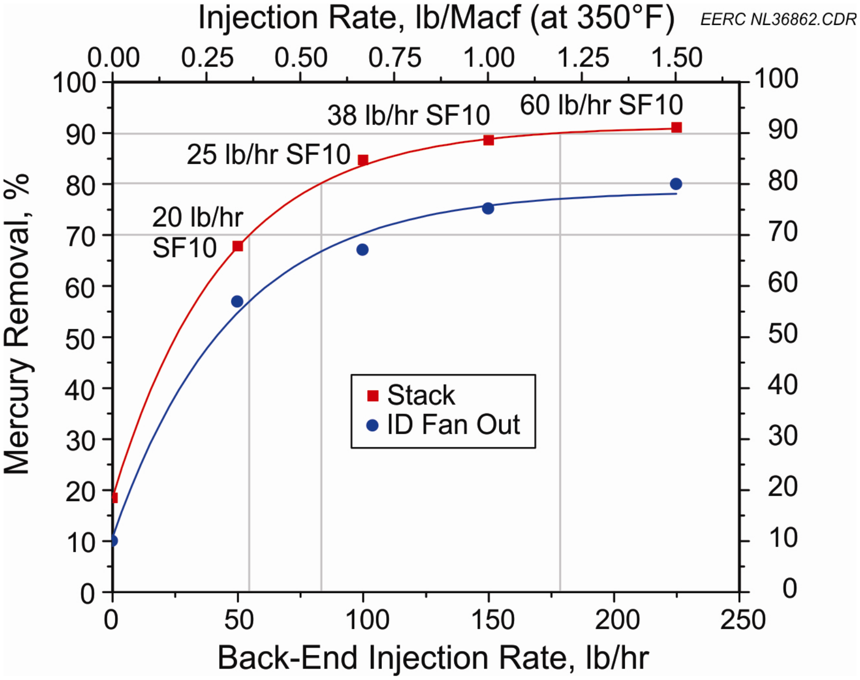


Figure 22. Summary of SF10–SB24 extended test mercury removal data.
The injection rates are for the entire unit.

BALANCE-OF-PLANT RESULTS

Unit operations were monitored by plant personnel during baseline, parametric, and extended test periods to ensure that the test program had little to no impact on the operation and integrity of the test unit. No effects directly related to the test program were documented for the duration of the project. Appendix F plots the plant data collected during the baseline, parametric, and extended test periods. During the parametric test period, plant personnel strived to maintain a constant full-load condition so that plant load did not positively or negatively affect mercury removal results.

Unit Performance

Table 10 displays the monthly averages for the plant data presented in Appendix F. The averages show that the unit operated consistently on a monthly basis and throughout the test program.

During the testing activities, the unit load was at or near full load for most of the time with the exception of short-duration (a couple hours) intervals in the middle of the night to reduce slagging in the furnace. Figures 23–25 include the load for the parametric, extended, and alternate SEA test periods, respectively. These low-load conditions were accounted for during data reduction and were left out of the data set when testing operations were ongoing at those times. During the test program, the unit went down on two occasions, August 7–10, and briefly on September 7.

SO_2, NO_x, and O_2 were generally consistent at full-load conditions. The plant O_2 data for the stack, ID fan outlet, and boiler exit were used to normalize the mercury data collected at the various locations so that the data could be compared at a consistent O_2 level of 3%.

Table 10. Plant Data Monthly Averages

Parameter	August Average	September Average	October Average	Overall Average
Air Preheater Differential Pressure, in. H_2O				
No. 22 Gas Side	10.45	10.62	10.38	10.48
No. 21 Gas Side	7.88	7.75	7.87	7.83
No. 22 Air Side	4.98	5.17	5.04	5.06
No. 21 Air Side	5.08	5.17	4.96	5.07
Fuel Flow, Klb/hr	867	822	847	845
Gross Load, MW	685	676	682	681
Mills in Service	7	7	7	7
O_2, %				
Stack O_2	5.87	6.44	6.10	6.14
No. 22 Boiler Exit	3.10	4.07	3.48	3.55
No. 21 Boiler Exit	2.72	2.71	2.70	2.71
Opacity, %				
No. 22	7.2	9.9	9.6	8.9
No. 21	8.2	4.4	4.0	5.5
Reagent Feed, gpm	53.4	45.0	34.3	44.2
Pumps in Service	2	2	2	2
Absorber Density	1.143	1.154	1.150	1.149
Stack NO_x, ppm	147	140	147	145
Stack SO_2, ppm	33	15	19	22
Temperature, °F				
No. 22 APH Inlet	846	832	828	835
No. 21 APH Inlet	842	828	826	832
Scrubber Inlet	347	335	327	336

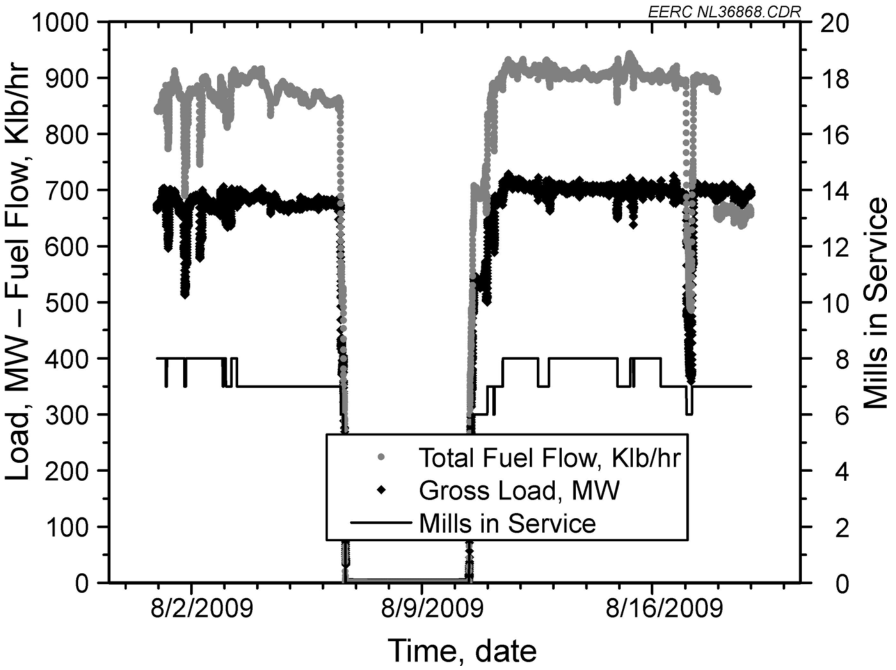


Figure 23. Load during parametric testing.

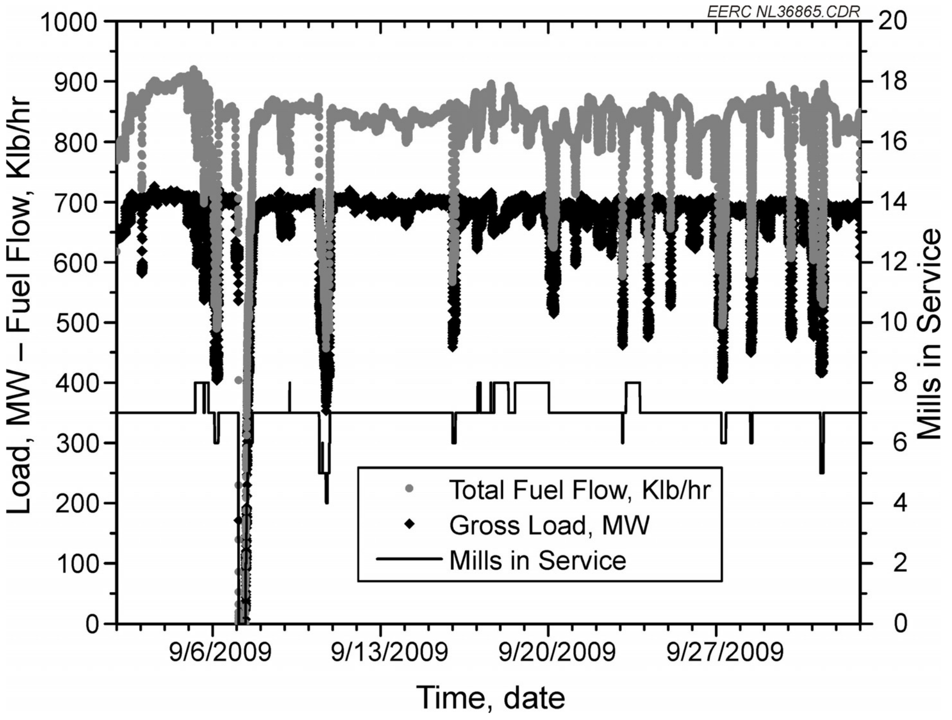


Figure 24. Load during extended testing.

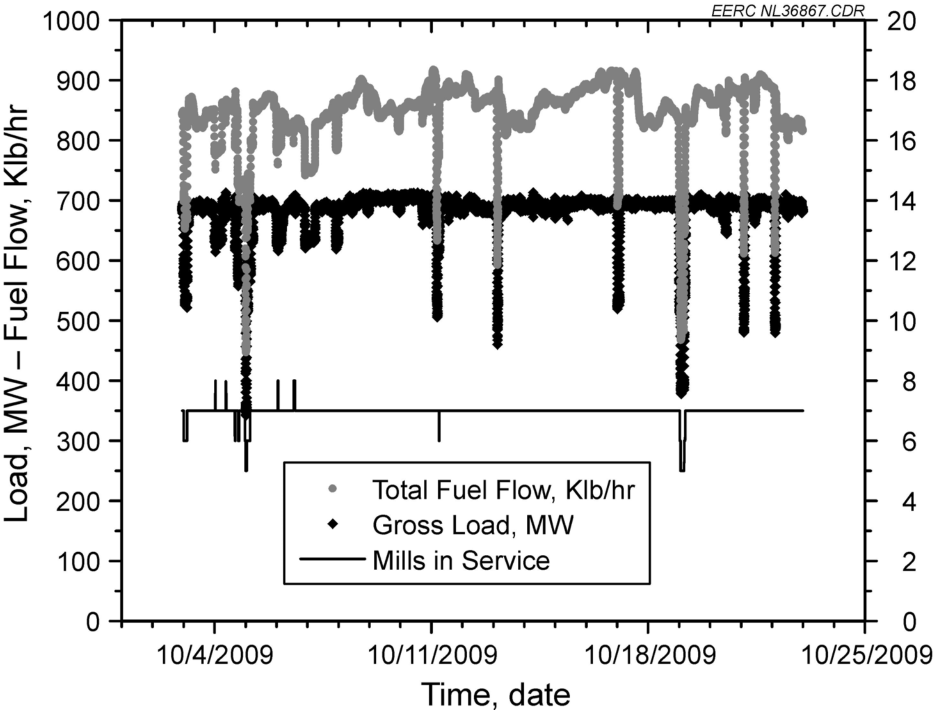


Figure 25. Load during alternate SEA testing.

Examination of the temperatures around the air preheaters and the differential pressures across the air preheaters show significant cycling on the gas side of Duct 22. Figures 26–28 show the temperatures, and Figures 29–31 show the differential pressures for the three test periods. The cycling is shown to be more severe during the extended test period in September. Although this may be an operational issue, it did not appear to affect sorbent injection or the resulting mercury capture. In October, there was a significant change in the air preheater differential pressure on the No. 22 gas side. After the change, the value remained consistent with the differential pressure on the No. 21 gas side.

Inspection of ESP operational data showed no difference between baseline conditions and injection conditions. Table 11 shows the average current and voltage for each of the fields along with spark rate. The data show that there is an alignment or control issue across the south side of Duct 22 (C Fields 1–4), but this did not change when injection was resumed. Comparison of baseline to injection conditions for all the fields indicates no discernible difference due to injection of sorbents or SEAs. Figures 32–35 show each of the four A fields (center of the duct) of Duct 22 comparing baseline conditions (left side of the graph before the break) to the higher level injection conditions (right side of the graph after the break). From these data, no discernible change can be seen due to injection conditions. The complete set of ESP operational data is presented in Appendix G.

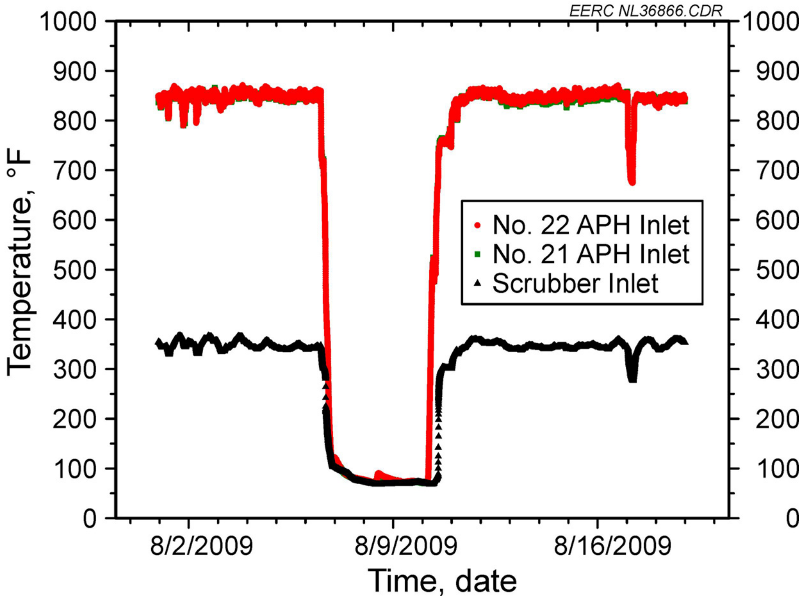


Figure 26. Flue gas temperatures during parametric testing.

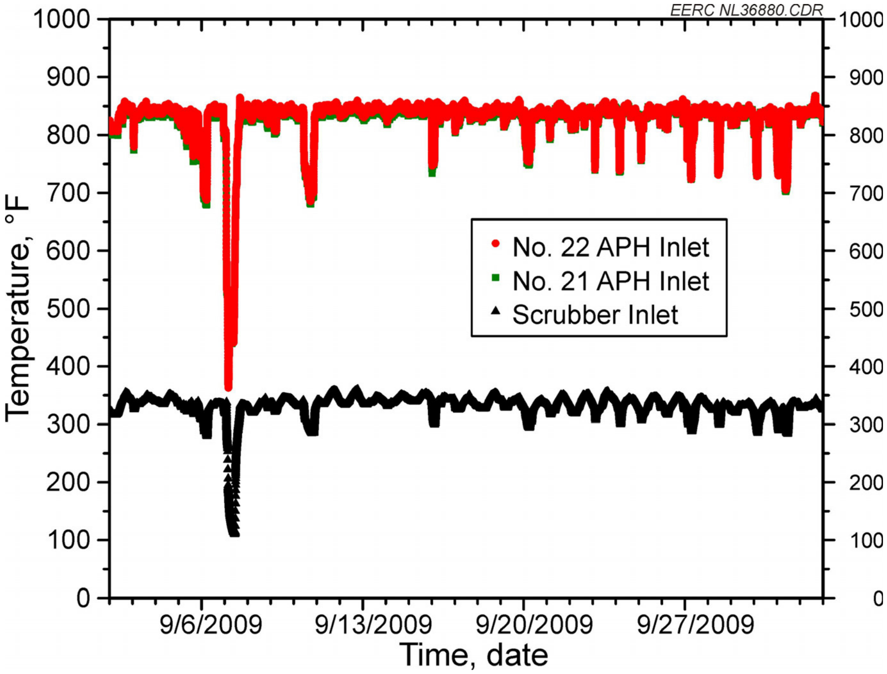


Figure 27. Flue gas temperatures during extended testing.

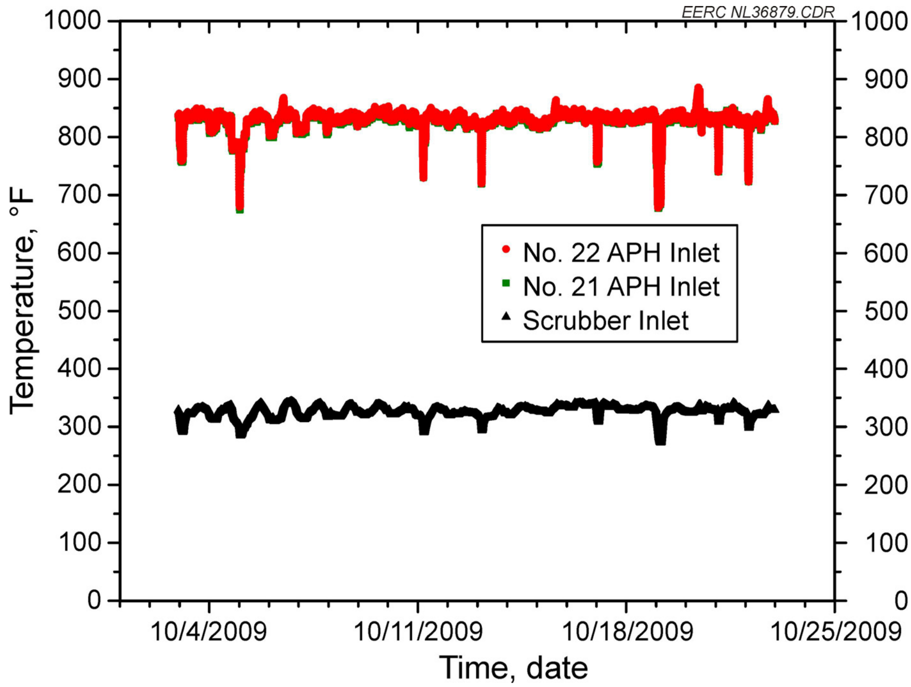


Figure 28. Flue gas temperatures during alternate SEA testing.

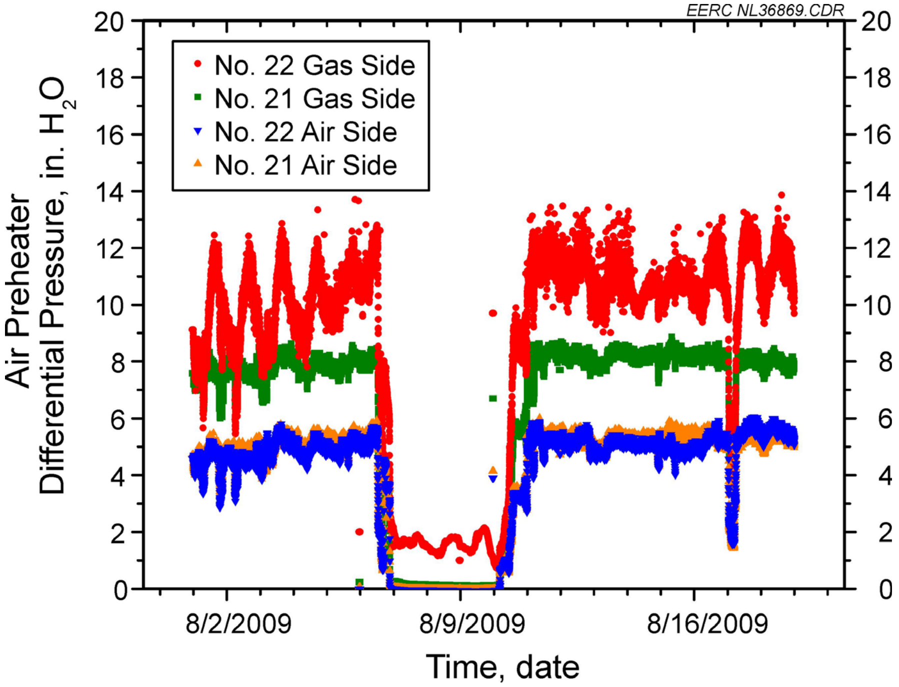


Figure 29. Air preheater differential pressures during parametric testing.

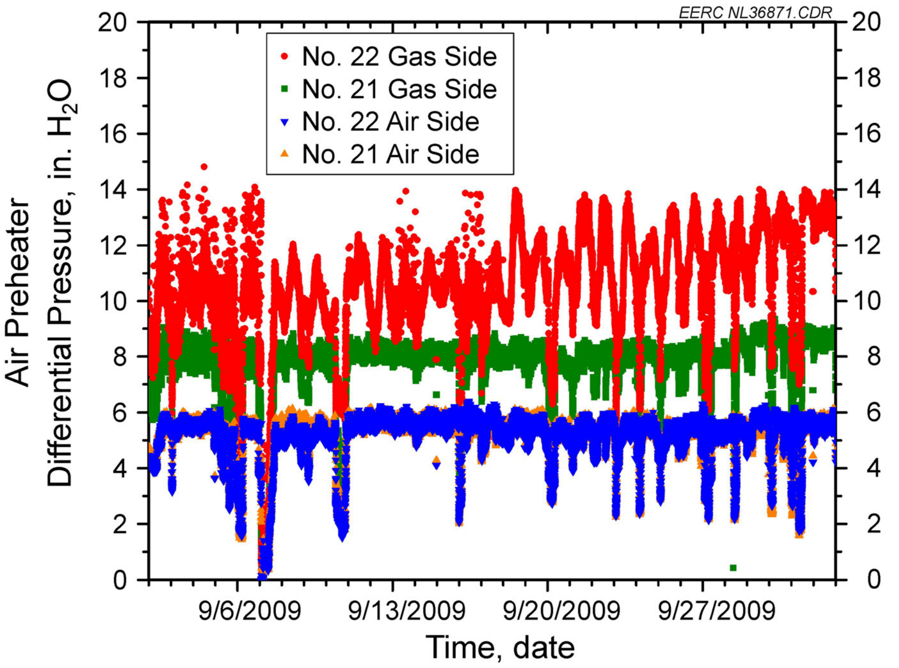


Figure 30. Air preheater differential pressures during extended testing.

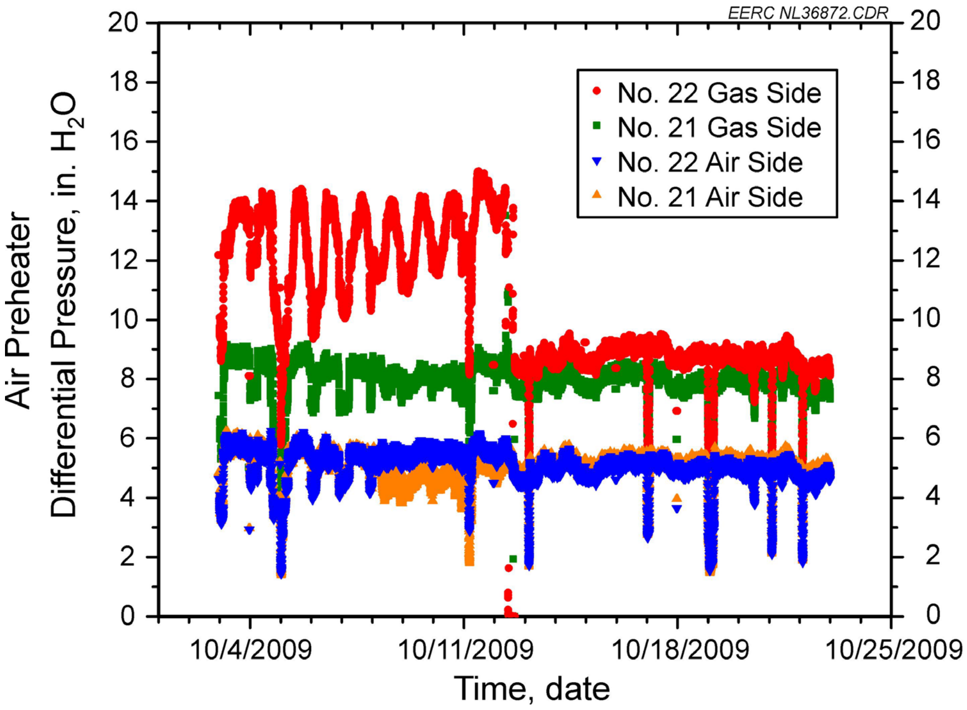


Figure 31. Air preheater differential pressures during the alternate SEA test period.

Table 11. Lodge Cottrell Operational Data

LC21							
		Baseline (Sept. 1–11)			With Injection (Sept. 12 – Oct. 2)		
		B	A	C	B	A	C
Field 1	mA	621	538	489	615	481	560
	kV	55	56	57	55	49	58
	Spark/min	1	5	15	0	5	7
Field 2	mA	-	613	633		637	646
	kV	-	49	54		50	54
	Spark/min	-	5	1		4	1
Field 3	mA	745	662	618	786	697	556
	kV	50	49	53	52	51	54
	Spark/min	2	12	10	1	10	7
Field 4	mA		841	925	925	853	903
	kV		52	54	53	53	54
	Spark/min		0	0	0	0	0
LC22							
		Baseline (Sept. 1–11)			With Injection (Sept. 12 – Oct. 2)		
		B	A	C	B	A	C
Field 1	mA		607	10		630	28
	kV		52	26		53	28
	Spark/min		8	30		4	30
Field 2	mA	766	672	266	746	605	245
	kV	51	51	49	52	50	48
	Spark/min	1	11	71	1	15	76
Field 3	mA	874	923	380	833	949	342
	kV	52	50	48	53	51	49
	Spark/min	0	1	26	0	0	27
Field 4	mA	897	854	456	893	629	361
	kV	51	51	49	52	53	49
	Spark/Min	0	0	8	0	4	10

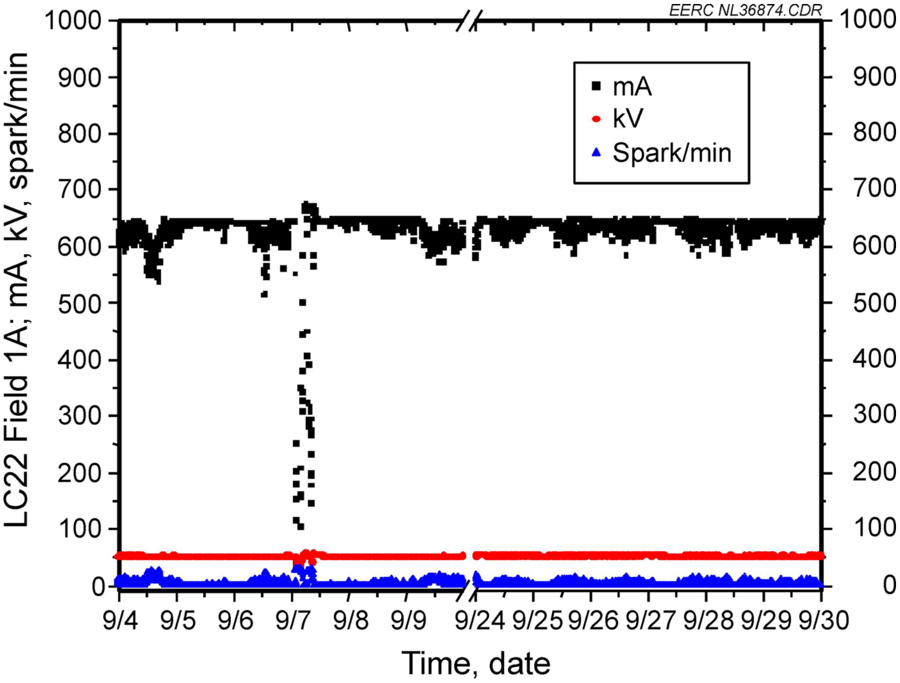


Figure 32. LC22 Field 1A, comparison of baseline and injection conditions.

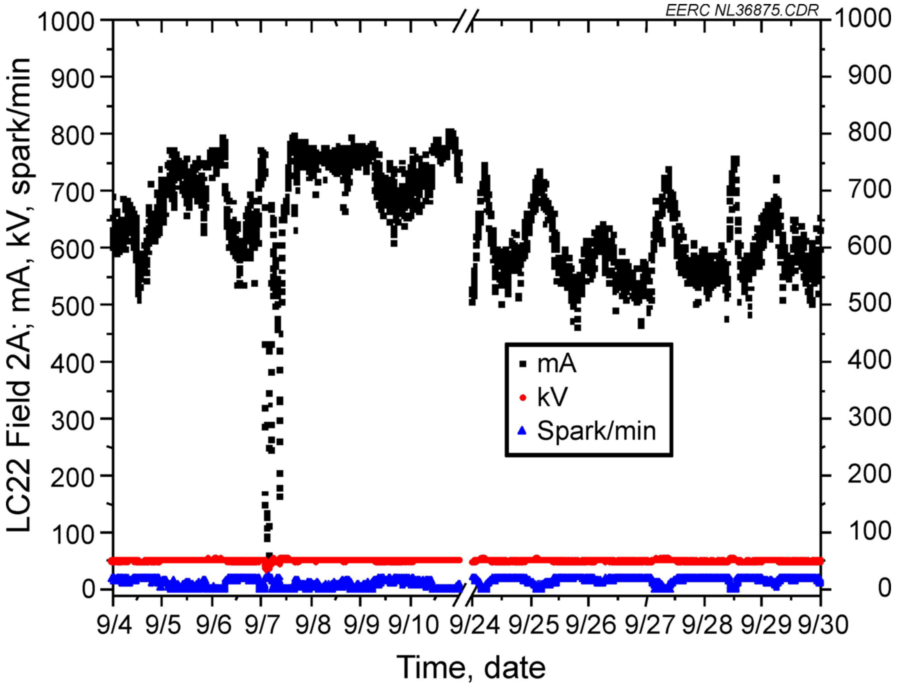


Figure 33. LC22 Field 2A, comparison of baseline and injection conditions.

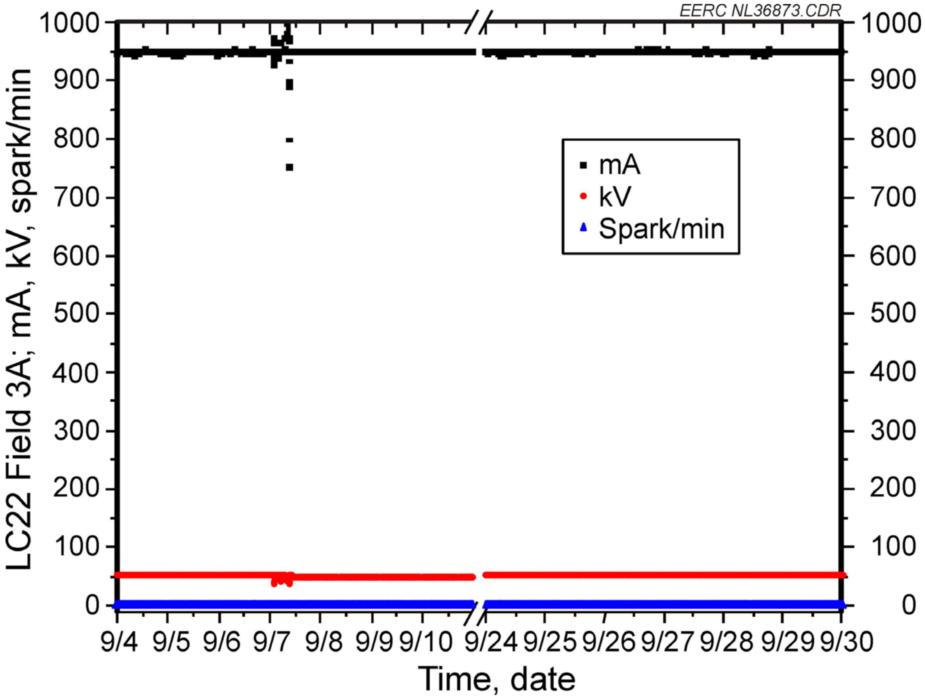


Figure 34. LC22 Field 3A, comparison of baseline and injection conditions.

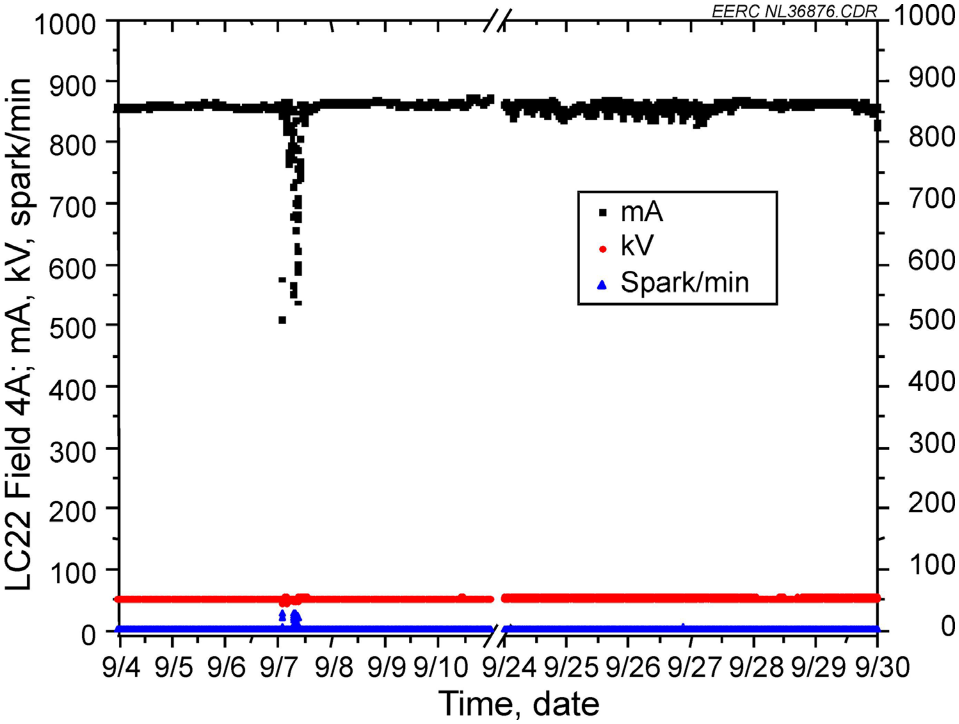


Figure 35. LC22 Field 4A, comparison of baseline and injection conditions.

ESP Ash Sampling

Sampling of ESP ash was conducted on a schedule determined and approved before the start of the test program. Samples were taken during baseline and extended testing to help determine the possible effect on injection and changes to ash chemistry, especially with regard to furnace injection. Samples were collected at the north and south Koppers and Lodge ESPs. The ash samples were analyzed for Cl and Br, Hg, and loss on ignition (LOI). The complete data set is presented in Appendix H. Table 12 displays the Cl and Br, Hg, and LOI data for the September baseline test period. The table shows that very little mercury is removed in the ESPs, which is consistent with flue gas baseline measurements. The Cl and Br ash concentrations in the Lodge ESPs are approximately twice the concentration found in the Koppers ESP. The LOI also follows a similar trend as the Cl and Br data, with a higher concentration found in the Lodge ESPs.

In addition to the baseline test period, ESP fly ash was collected during ET1, ET2, and ET3. Table 13 shows the analysis results for the fly ash collected during each extended test. The increase in the Hg fly ash concentrations is consistent with the flue gas mercury data and shows that mercury is being removed in both the Koppers and Lodge ESPs. The Cl and Br concentrations also increase over baseline conditions. The LOI in the Koppers ESPs is similar to baseline conditions, but there is a significant increase in the Lodge ESPs because of sorbent injection.

Table 12. Cl and Br, Hg, and LOI ESP Data During the September Baseline Test Period

Test Condition	ESP	9/8/09	9/9/09	9/11/09	Average
Hg		μg/g (dry)	μg/g (dry)	μg/g (dry)	μg/g (dry)
	K21	0.0295	0.0317	–	0.0306
	K22	0.0318	0.0355	0.0683	0.0452
	LC21	0.0274	0.0253	0.0214	0.0247
	LC22	0.0607	0.0456	0.0328	0.0464
Cl and Br		μg/g (dry)	μg/g (dry)	μg/g (dry)	μg/g (dry)
	K21	20.5	16.8	-	18.7
	K22	16.9	15.6	13.4	15.3
	LC21	34.2	33.9	36.4	34.8
	LC22	41.8	34.1	37.1	37.7
LOI		%	%	%	%
	K21	0.14	0.11	–	0.13
	K22	0.21	0.20	0.18	0.20
	LC21	0.44	0.34	0.49	0.42
	LC22	0.76	0.45	0.63	0.61

Table 13. Cl and Br, Hg, and LOI ESP Data During ET1, ET2, and ET3

Test Condition	ESP	ET1	ET2	ET3
Hg		µg/g (dry)	µg/g (dry)	µg/g (dry)
	K21	0.296	0.344	0.227
	K22	0.127	0.096	0.086
	LC21	6.64	5.45	12.4
	LC22	0.191	4.73	7.03
Cl and Br		µg/g (dry)	µg/g (dry)	µg/g (dry)
	K21	41.0	57.0	76.3
	K22	40.3	58.1	44.6
	LC21	145	294	265
	LC22	57.1	357	243
LOI		%	%	%
	K21	0.23	0.18	0.22
	K22	0.20	0.24	0.20
	LC21	2.0	3.94	4.39
	LC22	0.50	6.02	3.97

Figures 36–38 display the Hg, Cl and Br, and LOI in the ESP ash during the baseline and ET3 test conditions, respectively. During baseline conditions, both the Koppers and Lodge ESPs had very little Hg in the ash. Both the Koppers and Lodge ESPs exhibited an increase in Hg ash concentration during ET3. The Lodge ESPs had a significant increase in Hg ash concentration, which is consistent with the observed flue gas measurements that showed the majority of the Hg was removed by the Lodge ESPs. Figure 37 displays the total Cl and Br ash concentrations in the ESPs. The total Cl and Br in the ash increased in both the Koppers and Lodge ESPs during ET3. In Figure 38, the LOI remained consistent in the Koppers ESPs, but increased significantly in the Lodge ESPs. The increase in the Lodge ESPs is due to the sorbent injection ahead of the Lodge ESPs.

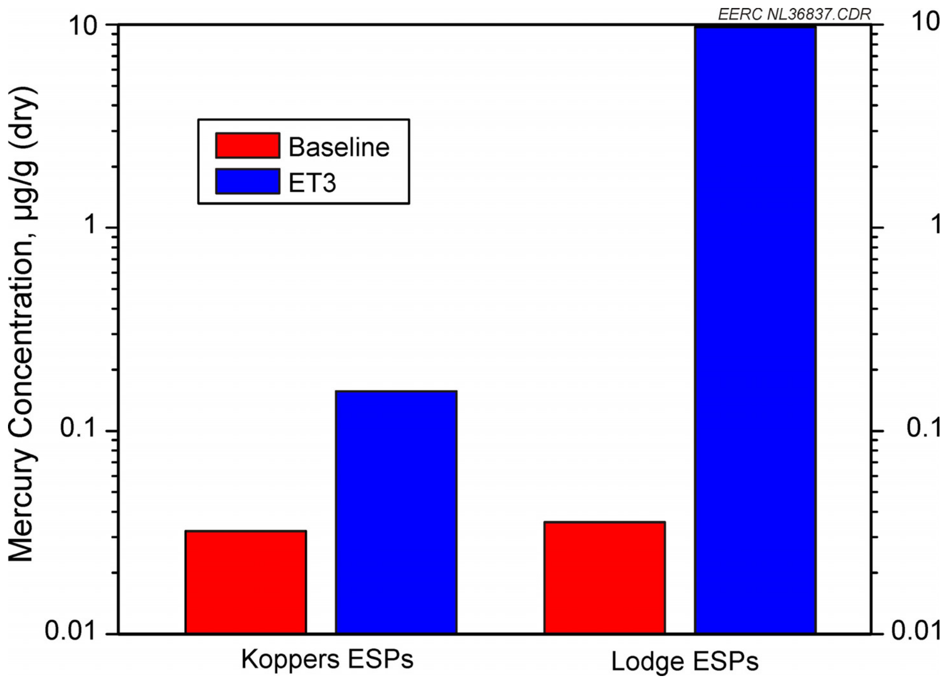


Figure 36. Baseline and ET3 mercury in ash concentration in the Koppers and Lodge ESPs.

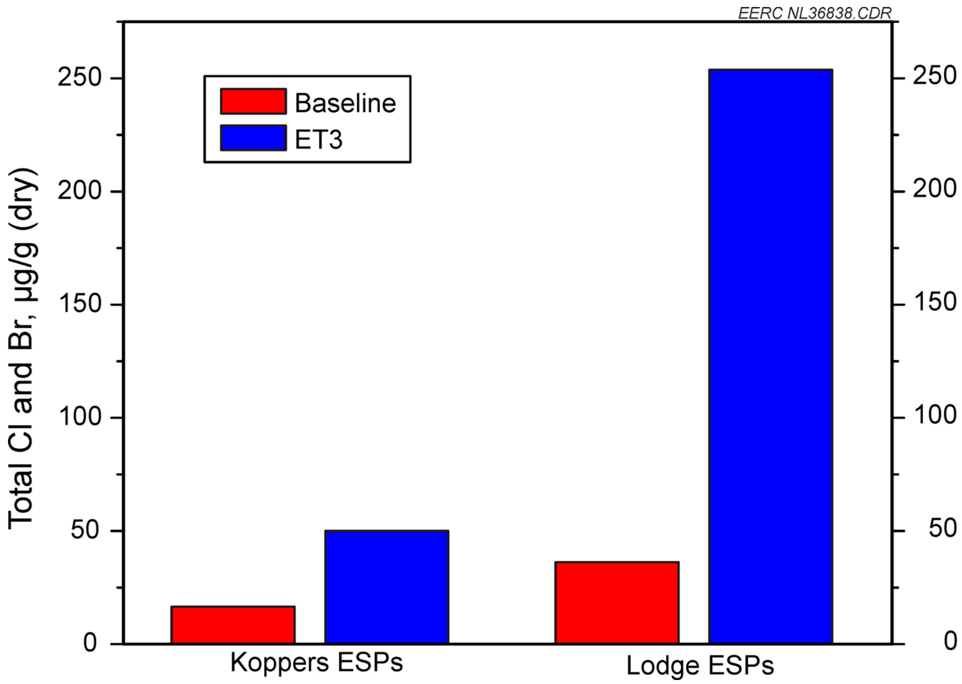


Figure 37. Baseline and ET3 total Cl and Br in ash concentration in the Koppers and Lodge ESPs.

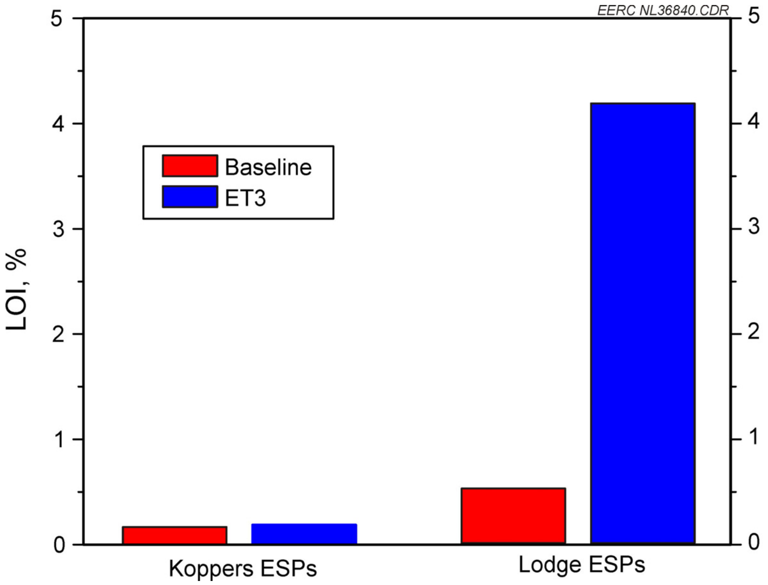


Figure 38. Baseline and ET3 ash LOI data for the Koppers and Lodge ESPs.

Scrubber Hg Sampling

Scrubber sampling was conducted daily during baseline and extended test conditions in order to determine the effects of sorbent injection on scrubber performance and by-products. Samples were collected from the reagent feed, recycle slurry, and gypsum. In the reagent feed and recycle slurry, mercury was analyzed for in both the liquid and solid portions. Appendix I presents the complete data set for all of the analyzed scrubber samples. Table 14 displays the scrubber analysis results for the reagent feed, recycle slurry, and gypsum during baseline test conditions. The baseline conditions show that the reagent feed is low in mercury. The majority of the mercury in the recycle slurry is in the solids. The gypsum mercury values are lower than the recycle slurry, which indicates that not all of the mercury ends up in the gypsum, but a significant amount remains in the slurry.

Table 15 displays the scrubber analysis results for the reagent feed, recycle slurry, and gypsum during Extended Tests (ET) 1–3. The extended test data show that the mercury concentration in the recycle slurry is lower than the baseline conditions. The reason for this is due to the increase in mercury removal across the ESPs during the extended tests compared to baseline conditions. The mercury concentration in the gypsum by-product is consistent with

Table 14. Baseline Mercury Analysis for Scrubber Reagent Feed, Recycle Slurry, and Gypsum

Test Condition	Sample	9/8/09	9/9/09	9/10/09	Average
Hg	Reagent Feed				
	Liquid, µg/L (wet)	<0.1	<0.1	<0.1	<0.1
	Solid, µg/g (dry)	0.023	0.026	0.024	0.024
	Recycle Slurry				
	Liquid, µg/L (wet)	0.23	0.30	0.40	0.31
	Solid, µg/g (dry)	3.76	3.34	3.39	3.50
	Gypsum				
	Solid, µg/g (dry)	2.32	0.85	0.98	1.38

Table 15. Mercury Analysis for Scrubber Reagent Feed, Recycle Slurry, and Gypsum During ET1, ET2, and ET3

Test Condition	Sample	ET1	ET2	ET3
Hg	Reagent Feed			
	Liquid, µg/L (wet)	<0.1	<0.1	<0.1
	Solid, µg/g (dry)	0.024	0.022	0.020
	Recycle Slurry			
	Liquid, µg/L (wet)	0.50	0.47	0.10
	Solid, µg/g (dry)	2.09	3.36	2.44
	Gypsum			
	Solid, µg/g (dry)	0.70	0.96	0.99

baseline data. The slightly lower recycle slurry mercury concentration and the similar gypsum mercury concentration indicate that there is no significant impact on scrubber mercury concentrations and by-products as a result of the SF10–SB24 extended tests.

Figure 39 displays the reagent feed solid, recycle feed solid, and gypsum Hg concentrations during baseline and ET3 test conditions, respectively. The reagent feed solid Hg concentration remained consistent for both test periods, which indicates a stable inlet supply with respect to Hg concentration. Both the recycle slurry solid and gypsum Hg concentrations decreased during ET3 compared to baseline conditions. The decrease is due to sorbent injection and the significant increase in mercury removal across the Lodge ESPs. The end result is that the overall amount of mercury entering the scrubber is lower than during baseline conditions, which corresponds to the lower concentrations in the recycle slurry and gypsum. This is beneficial because it reduces the concentration of the gypsum by-product and should not impact the sale of the by-product.

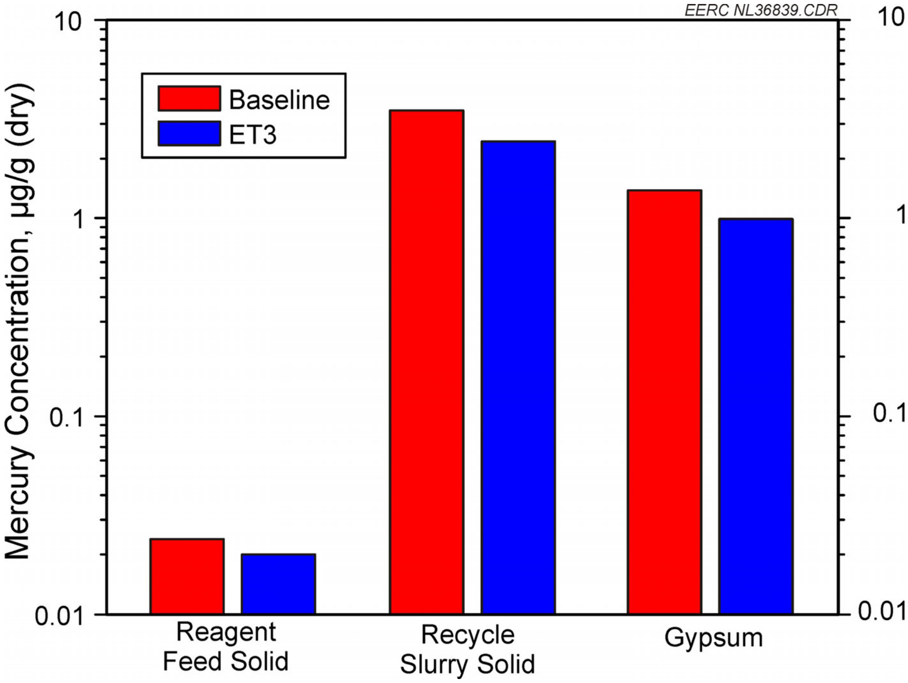


Figure 39. Baseline and ET3 scrubber Hg data.

Mass Balance

The mass balance of mercury and the M29 HAPs was calculated in order to determine the concentration of these elements in the by-product streams and to provide a set of data that can be compared to the flue gas data. In order to determine the mass balance over the unit, the following assumptions/estimations were made:

- Fly/bottom ash split of 75/25
- Koppers ESP efficiency of 85.7%
- Overall efficiency through the Lodge ESP of 99.3%
- Approximately 24% solids in the scrubber reagent feed

Additional process data included the values such as the percent ash in the coal, coal feed rate, sorbent injection rate, scrubber reagent feed rate, and stack flow rate. Analytical mercury and HAP data included in the mass balance calculations include flue gas measurements at each sampling location; coal concentrations, fly ash concentrations, and scrubber recycle slurry concentrations. All of the assumptions, process data, and analytical measurements are combined in order to get a better understanding of the fate of the mercury and HAPs across the system.

Mercury

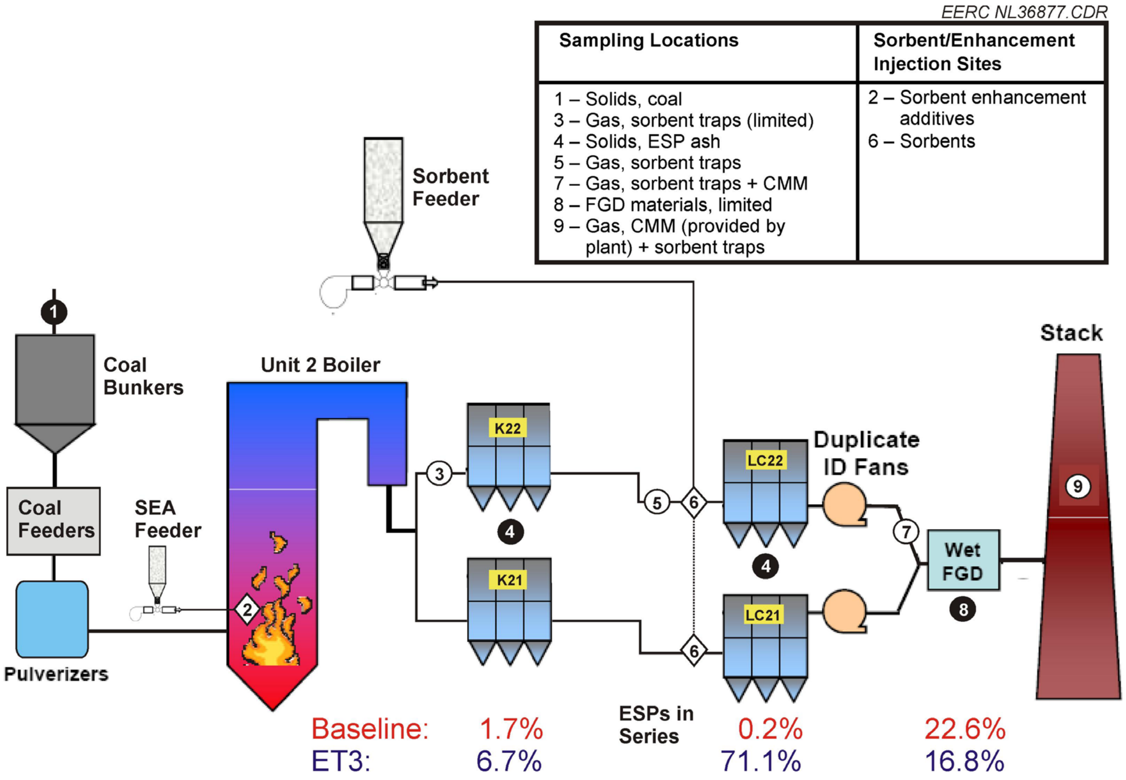
The complete mass balance tables for Hg are presented in Appendix J. The mercury mass balances in Table 16 show that the majority of the mercury is accounted for throughout the unit. The coal-to-ID-fan-out mass balance is excellent, with an agreement of ±13%. The coal-to-stack mass balance ranges from 91.2% to 121.0%, which shows that the values agree fairly well. The slightly larger difference is likely due to the estimates, assumptions, and flows that were made surrounding the scrubber. Obtaining accurate mass balances when including a scrubber is difficult because of varying reagent, recycle, and gypsum rates and the time required for chemical equilibrium at a set condition.

Figure 40 displays the mercury removal across each pollution control device during baseline and ET3 test conditions. These removals are based on the mass balance calculations and are, therefore, slightly different than the flue gas calculations. Even though the values are slightly different, the mass balance calculations are consistent with the flue gas data. The baseline data show that little to no mercury is removed across the Koppers and Lodge ESPs. The scrubber accounts for the majority of the baseline mercury removal with a removal of 22.6%.

During ET3, the mercury removal in the Koppers ESPs increases to 6.7%, and the mercury removal in the Lodge ESPs increases to 71.1%. This is a significant increase over baseline conditions and shows that the majority of the mercury is removed in the Lodge ESPs. The scrubber mercury removal decreases from 22.6% to 16.8% because most of the mercury is being removed in the Lodge ESPs. This reduction in scrubber mercury levels leads to less mercury in the scrubber by-products, as discussed above.

Table 16. Mercury Mass Balance for the Test Unit

	Balance (Hg out/Hg in), %			
	Baseline	ET1	ET2	ET3
Coal to ID Fan Outlet	112.6	92.0	105.6	104.6
Coal to Stack	121.0	91.2	95.7	105.9



Sampling Locations	Sorbent/Enhancement Injection Sites
1 – Solids, coal 3 – Gas, sorbent traps (limited) 4 – Solids, ESP ash 5 – Gas, sorbent traps 7 – Gas, sorbent traps + CMM 8 – FGD materials, limited 9 – Gas, CMM (provided by plant) + sorbent traps	2 – Sorbent enhancement additives 6 – Sorbents

Figure 40. Mercury removal across each pollution control device.

HAPs

The complete mass balance tables for the HAPs are presented in Appendix J. The coal-to-stack HAP mass balances during baseline and ET1 and are presented in Table 17. In general, the mass balances agree fairly well with the coal HAP concentrations. The majority of the mass balances are biased low, which is likely based on the scrubber estimations. Most of the baseline and ET1 mass balances are within 30%, except for Co, which is 50% lower than the coal concentration for both the baseline and ET1 mass balance calculations.

Table 17. HAP Mass Balances for the Test Unit

	Balance (HAP out/HAP in), %									
	As	Be	Cd	Co	Cr	Mn	Ni	Pb	Sb	Se
Baseline	82.7	76.6	83.3	45.9	68.5	68.8	71.4	70.1	76.3	109.7
ET1	110.9	72.8	106.0	45.1	72.3	69.8	75.1	74.7	80.4	126.1

Flue Gas Trace Metal Content

EPA Method 29 sampling was conducted during baseline and extended testing to determine any effect that sorbent injection may have on stack trace metal emissions. The sampling occurred at the south Lodge inlet and the stack. The coal samples on the corresponding sampling days were also analyzed to determine the HAP concentrations in the coal. These concentrations were converted to a flue gas basis using a combustion calculation spreadsheet. The results of the tests are summarized in Tables 18 and 19. Table 18 displays the baseline M29 results, and Table 19 displays the SF10–SB24 ET1 M29 results. The less-than values represent the EPA Method 29 reporting limits. The data show that the majority of the HAPs are removed in the Koppers ESPs, with additional removal in the Lodge ESPs and scrubber. Based on coal-to-stack measurements, >99% removal is obtained for all of the HAPs tested. Based on the data, sorbent injection for mercury control exhibits a very slight increase in removal for some of the HAPs tested.

Table 18. Baseline EPA Method 29 Test Results[a]

Baseline, μg/dNm^3 at 3% O$_2$									
	LC In					Stack			
	Coal	Particulate	Gaseous	Total	Removal, %	Particulate	Gaseous	Total	Removal, %
As	78.97	9.90	< 0.16	9.90	87.5	0.05	< 0.16	0.05	> 99.9
Be	18.31	1.52	< 0.21	1.52	91.7	< 0.06	< 0.21	< 0.27	> 99.9
Cd	5.72	0.55	< 0.02	0.55	90.4	0.02	< 0.02	0.02	99.7
Co	228.90	12.8	< 0.08	12.8	94.4	0.03	< 0.08	< 0.11	> 99.9
Cr	438.35	39.0	0.68	39.7	90.9	0.38	1.42	1.80	99.6
Mn	4097.37	392	1.34	393	90.4	0.74	4.25	4.99	99.9
Ni	317.03	29.0	0.37	29.4	90.7	0.25	1.17	1.41	99.6
Pb	232.34	26.6	0.49	27.1	88.3	0.21	0.58	0.79	99.7
Sb	13.73	1.59	< 0.21	1.64	88.1	< 0.06	< 0.21	< 0.27	> 99.8
Se	70.96	12.0	4.30	16.3	77.0	< 0.12	0.51	0.60	99.2

[a] Based on three samples.

Table 19. SF10-SB24 ET1 EPA Method 29 Test Results[a]

SF10–SB24 ET1, μg/dNm^3 at 3% O$_2$									
	LC In					Stack			
	Coal	Particulate	Gaseous	Total	Removal, %	Particulate	Gaseous	Total	Removal, %
As	68.67	9.97	< 0.16	9.97	85.5	< 0.05	<0.16	<0.21	>99.9
Be	18.31	1.44	< 0.21	1.45	92.1	< 0.06	<0.21	<0.27	>99.9
Cd	5.72	0.77	< 0.02	0.79	86.2	< 0.01	<0.02	<0.03	>99.8
Co	212.88	11.9	< 0.08	11.9	94.4	0.03	0.08	0.11	99.9
Cr	420.04	23.7	0.82	24.6	94.2	0.38	0.75	1.13	99.7
Mn	3664.75	319	3.14	322	91.2	0.66	3.86	4.52	99.9
Ni	295.29	28.2	1.12	29.3	90.1	0.22	1.18	1.40	99.5
Pb	225.47	27.2	0.97	28.2	87.5	0.21	0.66	0.87	99.6
Sb	13.73	1.70	< 0.21	1.74	87.3	< 0.06	<0.21	<0.27	>99.8
Se	69.82	11.6	73.1	84.7	−21.3	0.15	<0.41	0.51	99.3

[a] Based on three samples.

Dust Loading

EPA Method 5 sampling was conducted during baseline and extended testing to determine any effect that sorbent injection may have on increased stack particulate emissions. Table 20 displays the EPA M5 dust loading data collected during baseline and SF10–SB24 ET1 test conditions. The data are reported based on grams (g) per dry standard cubic feet (dscf) and in terms of grains (gr) per dscf. The data show little to no impact on the dust loading at the stack. Both stack values show minimal particulate loading exiting the stack.

Table 20. EPA M5 Dust Loading Data

	LC In		Stack	
	g/dscf	gr/dscf	g/dscf	gr/dscf
Baseline[a]	0.0095	0.1473	0.0000	0.0002
SF10–SB24 ET1[b]	0.0106	0.1643	0.0000	0.0002

[a] Based on two samples.

[b] Based on three samples.

Flue Gas Halogen Content

EPA M26a sampling was conducted during baseline, DARCO Hg-LH parametric testing, and SF10–SB24 ET3 to determine any the potential effect that SEA/sorbent injection may have on stack Cl, Br, and F emissions. The sampling occurred at the south LC inlet and the stack. The results of the M26a tests are summarized in Table 21. The baseline values at both the LC inlet and stack were below the detection limit of the method. The detection limits vary slightly because of variances in unit flow, coal composition, and load. These variables affect the flue gas composition and subsequent sampling detection limits. The DARCO Hg-LH values were also below the detection limit at both of the sampling locations. During the SF10–SB24 ET3, the value at the LC inlet was just above the detection limit with a concentration of 1.1 ppmv, but the stack value was below the detection limit. All of the flue gas F concentrations were below the detection limit for each of the test periods. These results show that there was no significant increase in Cl and Br emissions as a result of sorbent injection.

Table 21. EPA Method 26a Test Results

	Baseline[a]		DARCO Hg-LH 450 lb/hr[b]		SF10-SB24 ET3 38 lb/hr, 150 lb/hr[b]	
	ppmv					
	LC In	Stack	LC In	Stack	LC In	Stack
Total Cl and Br	<1.7	<1.5	<1.9	<1.4	1.1	<1.1
Total F	<1.4	<1.2	<1.5	<1.1	<1.3	<0.9

[a] Based on two samples.
[b] Based on one sample.

Effects of TIFI^{TM} Injection

At the request of plant personnel, a test was conducted to monitor the effects of TIFI injection on mercury control. TIFI is a furnace additive which is designed to reduce slag on the furnace boiler walls. In order to assess the effects of TIFI injection, SF10–SB24 was continuously injected at rates of 35.1 and 150 lb/hr for a 24-hr period before TIFI injection was turned on. This allowed the mercury removals across the system to reach a steady state and track the stability of the mercury removal before the TIFI injection was turned on. Figure 41 displays the CMM data for the 12-hr time period before and after TIFI injection was turned on. The figure shows that there is little or no effect (positive or negative) as a result of TIFI injection with respect to mercury removal. The CMM data remain consistent for the time duration before and after TIFI injection.

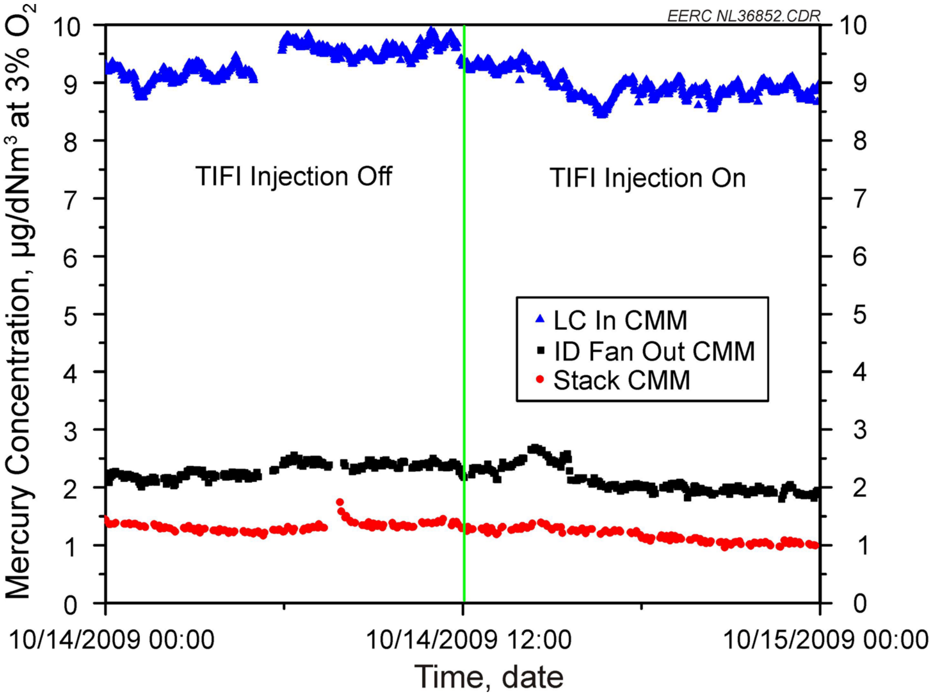


Figure 41. Effects of TIFI injection on sorbent injection for mercury removal. SF10–SB24 was injected into the entire unit at constant rates of 35.1 and 150 lb/hr, respectively.

Fly Ash Self-Heating

Because of the unique ESP–ESP–WFGD configuration and the sorbent injection location, the potential for self-heating exists. When sorbents are exposed to typical flue gas temperatures and an oxidizing atmosphere, they will oxidize and generate heat at a rate that is strongly temperature-dependent. If the heat cannot be dissipated, the temperature of the sorbent will rise and eventually reach the sorbent's ignition temperature. The risk for self-heating depends on many intensive and extensive properties including:

- Concentration of the sorbent in the fly ash.
- Thermophysical properties of the material.
- Heat generation characteristics of the material.
- Material volume and geometry.
- Temperature and thermal boundary conditions.

Figure 42 displays a risk assessment of self-heating based on flue gas temperature and sorbent content in the fly ash. Both flue gas temperature and sorbent content in the fly ash have a significant impact on the risk for self-heating. The use of hopper heaters will also increase the risk of self-heating and will, in general, shift the ignition risk area shown in Figure 42 downward and to the left as reflected by the shaded green area.

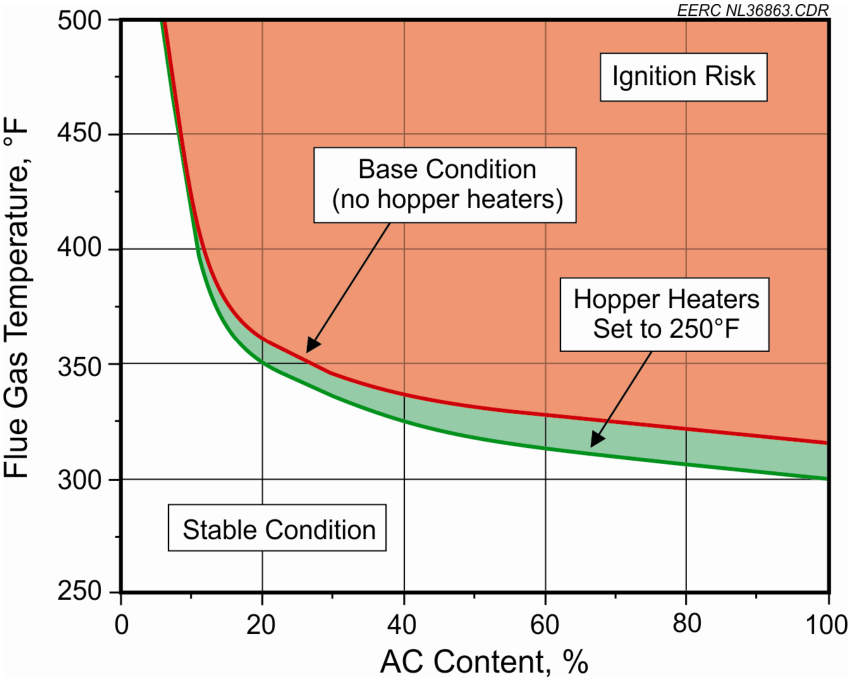


Figure 42. Self-heating risk plot based on an O_2 concentration of 6% and a surrounding ambient temperature of 70°F (red). Green area reflects the above conditions with the hopper heaters on at 250°F.

The flue gas temperature in the Lodge ESP is approximately 350°F. The sorbent content in the ash was calculated based on the amount of sorbent injected relative to the amount of ash entering the Lodge ESPs. The average amount of ash entering the Lodge ESPs is approximately 3500 lb/hr based on mass balance and dust loading calculations. Table 22 displays the sorbent content in the Lodge ESP ash for the range of injection rates tested during the project. At an injection rate of 150 lb/hr, the sorbent content in the ash is approximately 4.1%. At a flue gas temperature of 350°F, the percentage of sorbent in the ash presented in Table 22 maintains a stable condition based on Figure 42. At SB24 extended test injection rates ≤ 225 lb/hr, the self-heating risk is considered very low.

However, if AC alone were injected for mercury control, the higher injection rates could increase the potential for self-heating. For example, a DARCO Hg-LH injection rate of 475 lb/hr is required in order to obtain 80% mercury removal. At this injection rate, the ash sorbent content is approximately 12%, which is approximately three times higher than the ash sorbent content if SF10–SB24 is used for 80% mercury removal. Even though 12% is in the stable condition area, the higher sorbent content in the ash will have a slightly higher probability for self-heating. Generally speaking, fly ashes that contain 10% or more carbon are considered at-risk, and extra precautionary measures should be taken to monitor and evacuate the hoppers on a more frequent and managed basis.

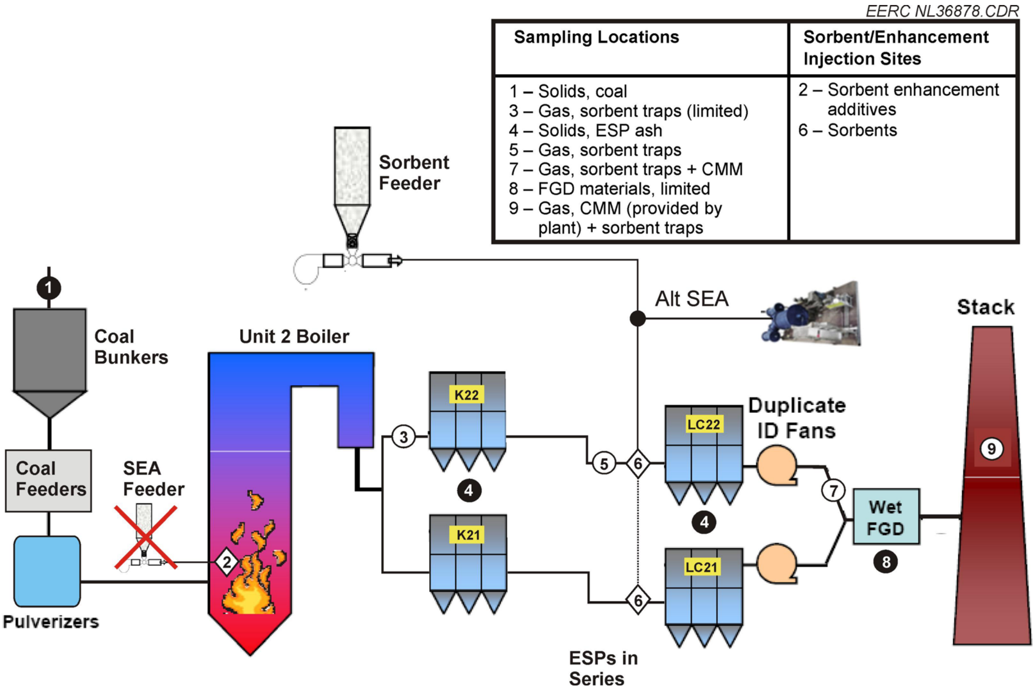
Table 22. Sorbent Content in Ash

Sorbent Injection Rate, lb/hr	Sorbent Content in Ash,[a] %
100	2.8
150	4.1
200	5.4
250	6.7
300	7.9
400	10.3
500	12.5
600	14.6

[a] Based on 3500 lb/hr ash entering the Lodge ESPs.

ALTERNATE SEA TESTING

In addition to the parametric and extended test plan, an extra project phase was added which focused on parametric and extended testing of a near-commercial prototype alternative SEA technology. This technology has the ability to introduce the SEA at any location within the flue gas stream and/or sorbent injection line to promote mercury capture. For these tests the alternative SEA was introduced along with the sorbent and then conveyed into the flue gas via the same splitter and injection lances previously described. Figure 43 displays the schematic which shows the alternate SEA injection setup as well as the sampling locations for the alternate SEA test period.



EERC NL36878.CDR

Sampling Locations	Sorbent/Enhancement Injection Sites
1 – Solids, coal 3 – Gas, sorbent traps (limited) 4 – Solids, ESP ash 5 – Gas, sorbent traps 7 – Gas, sorbent traps + CMM 8 – FGD materials, limited 9 – Gas, CMM (provided by plant) + sorbent traps	2 – Sorbent enhancement additives 6 – Sorbents

Figure 43. Alternate SEA injection schematic.

Alternate SEA Parametric Tests

Parametric tests were performed to determine the effectiveness of the alternate SEA technology and to determine the effectiveness of different RLP Energy SEAs. Each parametric test was performed long enough for the CMMs to reach an apparent steady state, typically for durations of 0.5 to 2 hours. Injections were started at relatively low rates and then systematically increased to higher injection rates in order to minimize potential memory effects from the higher injection rates. ST measurements were also periodically collected to compare the ST values to the CMM values.

The first alternate SEA technology tested was SC1–SB24. Figure 44 displays the percent mercury removals during the injection of SC1–SB24. Because of difficulties with the system and keeping the convey lines free of moisture, the data were collected over several days. The first SC1–SB24 injection rates of 9.6 and 150 lb/hr yielded mercury removals of 62.08% and 71.89% at the ID fan outlet and stack, respectively. As the SC1–SB24 injection rates were increased, mercury removal improved only slightly. A maximum mercury removal of 78.63% was obtained at SC1–SB24 injection rates of 28.8 and 150 lb/hr, respectively. Most of the mercury removal occurred in the Lodge ESPs, with approximately an additional 10% mercury removal in the scrubber.

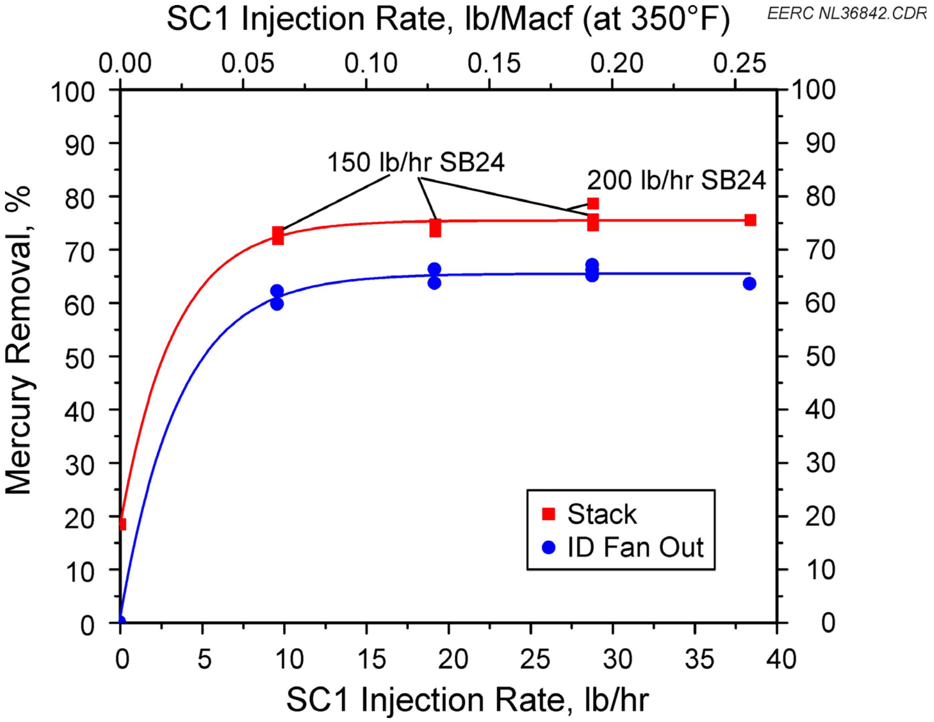


Figure 44. ID fan outlet and stack percent mercury removals as a function of SC1–SB24 injection rates. Injection rates are for the entire unit.

Two other alternate SEAs, SC3 and SC6, were also briefly tested. The SC3–SB24 combination was able to achieve an ID fan out mercury removal of 77.4% at injection rates of 19.3 and 75 lb/hr. This technology was only injected on the south side of the test unit, so representative stack data could not be obtained. When the SC6–SB24 was injected into the entire unit at rates of 23.5 and 150 lb/hr, the ID fan out and stack mercury removals were 53.2% and 61.7%, respectively.

Alternate SEA Extended Test

One 8-hr extended test was conducted with the SC1–SB24 technology to determine the effectiveness of the technology for an extended test period. The SC1–SB24 injection rates used for this test period were 19.7 and 150 lb/hr, respectively. Figure 45 displays the CMM mercury data for the duration of the extended test along with the plant load. The CMM data show that the mercury removal at both the ID fan outlet and stack remained consistent throughout the test period. The average mercury removals at the ID fan outlet and stack were 65.98% and 70.38%, respectively. These removals are consistent with the parametric data presented in Figure 44.

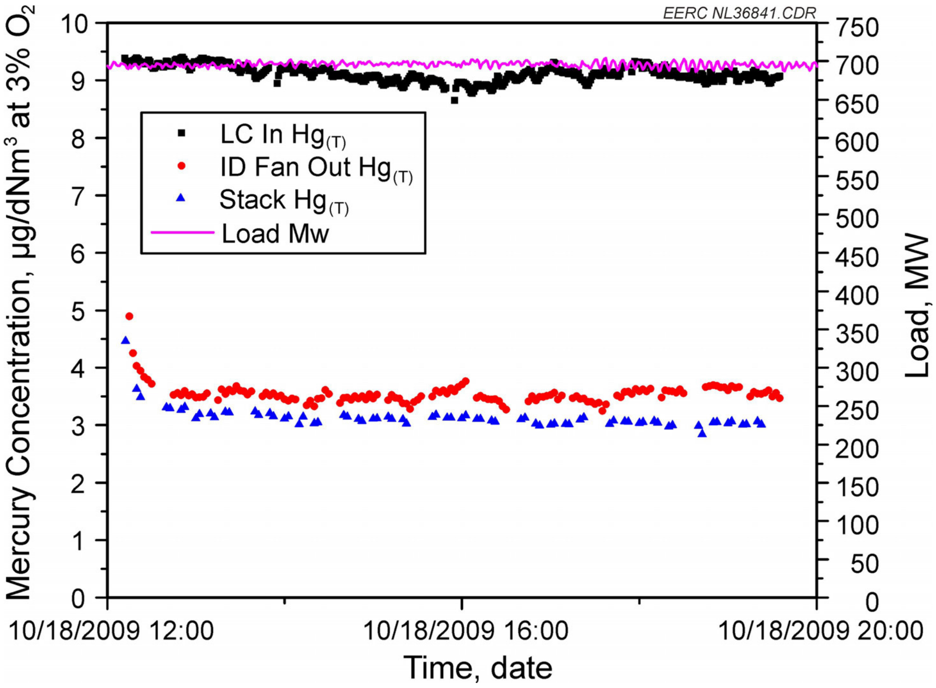


Figure 45. SC1–SB24 extended test CMM data. SC1 and SB24 injection rates were 19.7 and 150 lb/hr, respectively. Injection rates are for the entire unit.

Comparison of Alternate SEA Technology

Figure 46 displays the alternate SEA injection results along with the other best technologies that were tested. The figure shows that the alternate SEA mercury removal results are much higher than the AC mercury removals at equivalent injection rates. The alternate SEA technology with the poorest performance had approximately a 10% higher mercury removal than the AC technologies at the same injection rates. At equivalent injection rates, the SC1–SB24 and SC3–SB24 mercury removal results are approximately 10% lower than the SF10–SB24 mercury removal results, but are 30%-35% higher than the DARCO Hg-LH and DARCO Hg-CC mercury removal results. This shows that the alternate SEA technology performs much better than treated carbons, but in its current design and state of operation not quite as well as the SF10–SB24 technology. Based on the limited data, the alternate SEA technology shows that it is a feasible alternative to treated AC technologies, but currently does not perform as well as the best SEA–sorbent-based technologies. Further improvements on design and operation of the alternate SEA are expected to improve on these results.

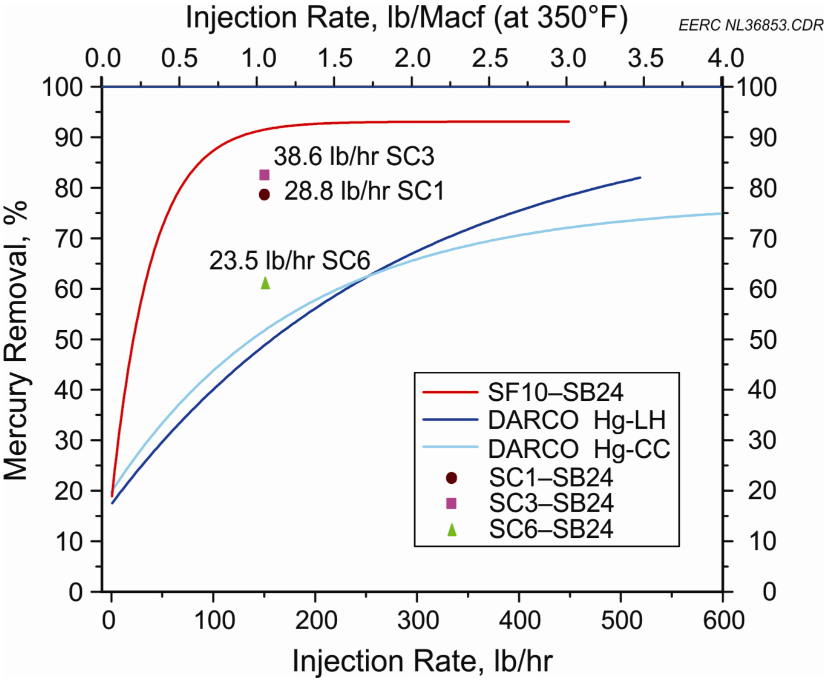


Figure 46. Summary of alternate SEA injection results compared to other technologies tested. Note: SC3–SB24 mercury removal was increased by 5% to reflect stack mercury removals. Injection rates are for the entire unit.

Leaching Results

Coal combustion product (CCP) samples from both the north and south Lodge ESPs were evaluated for the leachability of select constituents using the "Integrated Framework for Evaluating Leaching in Waste Management and Utilization of Secondary Materials" (4) method which has been adopted by EPA for the evaluation of CCPs. A complete, detailed discussion of the leachate results is presented in Appendix K.

Table 23 displays the maximum HAP leachate concentrations that were measured across the range of pHs under the different test conditions. The data show that the maximum leachate concentrations are much lower than the TCLP limits regardless of the leachate pH. The maximum leachate concentrations for each HAP generally occurred toward either the more acidic or basic sides of the pH range.

In addition to the HAPs discussed above, concentrations of select nonmetal analytes of interest, including Br, Cl, F, and SO_4, were also determined in the leachate samples. The Br, Cl, and F leachate concentrations remained low for each of the CCP samples. The SO_4 leachate concentrations were higher than the other nonmetals, with a range of approximately 100–2700 mg/L.

Table 23. TCLP Limits and Maximum Leachate Concentrations for Select HAPs

	Sb, mg/L	As, mg/L	Be, mg/L	Cd, mg/L	Cr, mg/L	Co, mg/L	Pb, mg/L	Mn, mg/L	Hg, mg/L	Ni, mg/L	Se, mg/L
TCLP Limit	–	5	–	1.0	5.0	–	5.0	–	0.2	–	1.0
Baseline	<0.005	0.013	0.0013	0.0004	0.44	0.0132	<0.01	<0.05	<0.00005	0.0775	0.33
SF10-SB24 ET1	<0.005	0.01	0.0013	0.0003	0.31	0.0116	<0.01	<0.05	<0.00005	0.117	0.74

CONCLUSIONS

Baseline, parametric, and extended tests were successfully conducted at the test unit for several mercury control technologies. The baseline test period indicated that the flue gas mercury concentration exhibits some variance but remains within a consistent range. Parametric test results indicated that SF10–SB24, SF10–SB21, and DARCO Hg-LH were able to achieve the target mercury removal of ≥ 80%. Because of its strong performance, SF10–SB24 was chosen for four extended tests, which targeted mercury removals of 60%, 70%, 80%, and >90%. The targeted mercury removal was exceeded for each of the extended tests.

In general, the ST measurements agreed well with the CMMs and typically were within a relative difference of 10%. The coal and inlet ST data agreed fairly well and demonstrated that either method can be used to determine the inlet flue gas mercury concentration. The baseline mercury removals indicated that little to no mercury was removed in the Koppers and Lodge ESPs, and 18.5% was removed in the scrubber for a total baseline mercury removal of 18.5%.

During SF10–SB24 injection, the Lodge ESPs captured most of the flue gas mercury with an additional 5%–15% capture across the scrubber. During SF10–SB24 ET3, approximately 6.7% of the mercury was removed in the Koppers ESPs, 71.1% across the Lodge ESPs, and 16.8% across the scrubber for a total mercury removal of 94.6% based on mass balance calculations. Since the majority of the mercury is removed in the Lodge ESPs before it enters the scrubber, the total mercury in the scrubber and scrubber by-products decreases because of less mercury entering the scrubber as compared to baseline conditions. This is beneficial when considering scrubber by-products as a salable commodity.

The halogen (M26a) and trace element (M29) data showed little to no impact in stack emissions as a result of sorbent injection. The M26a data showed that the stack halogen emissions were less than 1.1 ppmv. The stack M29 data demonstrated >99% removal during baseline and injection testing periods. The Koppers ESPs removed 75%–95% of the trace metals, with the rest of the removal occurring across the Lodge ESPs and scrubber. The particulate (M5) data did not show any significant effect (positive or negative) due to sorbent injection when the data were compared to baseline results.

The impacts of TIFI injection on mercury removal were also evaluated. SF10–SB24 injection with and without the addition of the TIFI furnace additive demonstrated that TIFI does not have any impact (positive or negative) on mercury removal.

The self-heating risk in the Lodge ESP hoppers is minimal at low injection rates. The SF10–SB24 reduces the self-heating risk because the amount of injected carbon-based sorbent is minimized because of the performance of the technology. However, the use of treated carbons (i.e. from Norit Americas) will increase this risk as more than twice as much sorbent is needed to achieve similar mercury removals.

The alternate SEA technology was successfully tested during parametric and full-scale tests and demonstrated that this approach yields mercury removals up to 35% higher than treated AC injection at equivalent injection rates. When compared to the best front- and back-end approach, the alternate SEA technology demonstrates removals that are approximately 10% lower at equivalent injection rates. The parametric tests indicated that 70%–75% mercury removal was feasible at low injection rates. The 8-hr extended test demonstrated that the technology was able to obtain consistent mercury removals for an extended period of time.

In terms of testing the alternate SEA, the biggest challenge was testing within the limitations of the temporary rubber hose that was installed for sorbent injection. Future testing/installations need to overcome condensation issues by using metal piping and operating at higher temperatures, which are expected to result in improved performance.

The leachate data showed that 95%–99% of the HAP elements remained in the CCP samples and that the baseline sample data were similar to the ET1 sample data. The maximum leachate values were significantly below the TCLP leachate limits.

REFERENCES

1. Pavlish, J.H.; Hamre, L.L.; Laudal, D.L.; Holmes, M.J.; Weber, G.F.; Hajicek, D.R.; Pavlish, B.M. *Technical Review of Mercury Options for Canadian Utilities – A Report to the Canadian Council of Ministers of the Environment*; Final Report to the Canadian Council of Ministers of the Environment; Contract No. 348-2005; EERC Publication 2005-EERC-03-07; Energy & Environmental Research Center: Grand Forks, ND, March 2005.

2. Olson, E.S.; Laumb, J.D.; Benson, S.A.; Dunham, G.E.; Sharma, R.K.; Mibeck, B.A.; Miller, S.J.; Holmes, M.J.; Pavlish, J.H. An Improved Model for Flue Gas–Mercury Interactions on Activated Carbons. Presented at the DOE–EPRI–EPA–A&WMA Power Plant Air Pollutant Control "Mega" Symposium, Washington, DC, May 19–22, 2003.

3. Pavlish, J.H.; Thompson, J.S.; Hamre, L.L. *Confidential Site-Specific Test Plan: Full-Scale Testing to Evaluate Mercury Control Options at the Centralia Generating Station*; Oct 2009.

4. Kosson, D.S.; van der Sloot, H.A.; Sanchez, F.; Garrabrants, A.C. An Integrated Framework for Evaluating Leaching in Waste Management and Utilization of Secondary Materials. *Environ. Eng. Sci.* **2002**, *19* (3), 159–203.

APPENDIX A

TEST COAL DATA

TEST COAL DATA

Coal samples were subjected to proximate, ultimate, Btu, Hg, and Cl and Br analysis. Tables A-1–A-6 contain the complete results of these analysis. The samples were belt samples, which were collected with an automated coal belt sampler. The samples are reported on an as-received basis.

Table A-1. Coal Analysis, as-received basis unless otherwise noted

Sample Date: Sample Time:	8/5/09 1800–0600	8/6/09 1800–0600	8/11/09 1800–0600	8/12/09 1800–0600	8/13/09 1800–0600	8/14/09 1800–0600	8/15/09 1800–0600	8/16/09 1800–0600	8/17/09 1800–0600
Hg, ppm (dry)	0.0874	0.1060	0.0570	0.0715	0.1160	0.0732	0.0890	0.0767	0.0616
Halogens,[a] ppm (dry)	20.3	14.4	10.0	14.4	19.8	12.0	13.2	13.2	9.9
Proximate, wt%									
Moisture	31.20	31.30	32.20	31.00	32.40	33.40	32.40	32.70	32.00
Volatile Matter	24.89	24.53	24.54	24.41	25.18	23.82	23.79	23.97	24.00
Fixed Carbon	39.51	39.89	39.56	39.13	38.35	39.36	39.66	39.47	40.24
Ash	4.39	4.28	3.70	5.46	4.08	3.42	4.15	3.86	3.76
Total	99.99	100.00	100.00	100.00	100.01	100.00	100.00	100.00	100.00
Ultimate, wt%									
Carbon	48.36	47.86	48.03	47.54	47.35	47.07	47.59	46.92	48.00
Hydrogen[b]	3.15	3.09	3.12	3.06	3.07	2.98	2.96	2.97	3.00
Oxygen in Fuel[b]	11.87	12.42	12.01	11.95	12.11	12.33	11.84	12.72	12.34
Nitrogen	0.62	0.61	0.58	0.58	0.58	0.56	0.56	0.58	0.57
Sulfur	0.41	0.44	0.35	0.41	0.41	0.23	0.49	0.25	0.34
Moisture	31.20	31.30	32.20	31.00	32.40	33.40	32.40	32.70	32.00
Ash	4.39	4.28	3.70	5.46	4.08	3.42	4.15	3.86	3.76
Total	100.00	100.00	99.99	100.00	100.00	99.99	99.99	100.00	100.01
Heating Value, Btu/lb	8060	8074	8029	7936	7940	7914	7951	7890	7995

[a] Does not include fluorine.

[b] Moisture not included in hydrogen and oxygen values.

Table A-2. Coal Analysis, as-received basis unless otherwise noted

Sample Date: Sample Time:	8/18/09 1800–0600	9/7/09 1800–0600	9/8/09 1800–0600	9/9/09 1800–0600	9/10/09 1800–0600	9/11/09 1800–0600	9/13/09 1800–0600	9/14/09 1800–0600	9/15/09 1800–0600
Hg, ppm (dry)	0.0817	0.0903	0.0772	0.0848	0.0690	0.0769	0.0645	0.0677	0.0648
Halogens,[a] ppm (dry)	14.0	16.8	17.5	12.6	19.9	9.7	12.7	13.1	12.0
Proximate, wt%									
Moisture	31.60	30.70	30.40	30.20	30.10	29.10	29.60	29.70	30.10
Volatile Matter	24.40	23.96	24.64	24.90	24.92	24.84	24.89	25.27	25.59
Fixed Carbon	39.76	41.81	41.68	41.11	41.10	42.76	42.02	41.73	40.88
Ash	4.25	3.53	3.28	3.79	3.88	3.30	3.49	3.30	3.43
Total	100.01	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Ultimate, wt%									
Carbon	47.52	50.42	50.53	50.29	50.27	51.59	50.83	50.96	50.38
Hydrogen[b]	3.02	3.38	3.50	3.32	3.30	3.23	3.38	3.24	3.43
Oxygen in Fuel[b]	12.67	11.04	11.37	11.51	11.56	11.89	11.79	11.92	11.77
Nitrogen	0.55	0.65	0.64	0.60	0.59	0.62	0.60	0.60	0.59
Sulfur	0.39	0.28	0.29	0.28	0.30	0.28	0.30	0.28	0.30
Moisture	31.60	30.70	30.40	30.20	30.10	29.10	29.60	29.70	30.10
Ash	4.25	3.53	3.28	3.79	3.88	3.30	3.49	3.30	3.43
Total	100.00	100.00	100.01	99.99	100.00	100.01	99.99	100.00	100.00
Heating Value, Btu/lb	7954	8353	8415	8415	8411	8563	8492	8508	8454

[a] Does not include fluorine.

[b] Moisture not included in hydrogen and oxygen values.

Table A-3. Coal Analysis, as-received basis unless otherwise noted

Sample Date:	9/16/09	9/17/09	9/18/09	9/19/09	9/20/09	9/21/09	9/22/09	9/23/09	9/24/09
Sample Time:	1800–0600	1800–0600	1800–0600	1800–0600	1800–0600	1800–0600	1800–0600	1800–0600	1800–0600
Hg, ppm (dry)	0.0765	0.0839	0.0675	0.0864	0.0768	0.0677	0.0814	0.0792	0.1040
Halogens,[a] ppm (dry)	14.6	12.0	17.5	15.3	12.7	12.9	15.5	16.3	13.7
Proximate, wt%									
Moisture	30.10	31.80	28.80	30.50	30.00	30.40	32.00	31.10	31.60
Volatile Matter	25.06	24.32	24.89	25.61	25.23	25.55	24.74	25.01	24.59
Fixed Carbon	41.18	39.72	38.63	40.39	40.98	39.74	39.61	39.99	39.60
Ash	3.66	4.16	7.69	3.50	3.79	4.31	3.65	3.90	4.21
Total	100.00	100.00	100.01	100.00	100.00	100.00	100.00	100.00	100.00
Ultimate, wt%									
Carbon	50.79	48.41	47.43	50.30	50.40	49.82	48.39	49.90	48.76
Hydrogen[b]	3.19	3.28	3.11	3.31	3.27	3.19	3.29	3.03	3.13
Oxygen in Fuel[b]	11.33	11.40	12.01	11.50	11.66	11.39	11.75	11.20	11.38
Nitrogen	0.62	0.59	0.61	0.61	0.62	0.58	0.60	0.58	0.59
Sulfur	0.30	0.37	0.35	0.28	0.27	0.31	0.31	0.29	0.32
Moisture	30.10	31.80	28.80	30.50	30.00	30.40	32.00	31.10	31.60
Ash	3.66	4.16	7.69	3.50	3.79	4.31	3.65	3.90	4.21
Total	99.99	100.01	100.00	100.00	100.01	100.00	99.99	100.00	99.99
Heating Value, Btu/lb	8390	7980	7980	8374	8397	8299	8168	8243	8104

[a] Does not include fluorine.

[b] Moisture not included in hydrogen and oxygen values.

Table A-4. Coal Analysis, as-received basis unless otherwise noted

Sample Date: Sample Time:	9/25/09 1800–0600	9/26/09 1800–0600	9/27/09 1800–0600	9/29/09 1800–0600	9/30/09 1800–0600	10/2/09 1800–0600	10/3/09 1800–0600	10/4/09 1800–0600	10/5/09 1800–0600
Hg, ppm (dry)	0.0803	0.0749	0.0825	0.1010	0.0647	0.0760	0.0766	0.1020	0.0721
Halogens,[a] ppm (dry)	12.7	12.0	18.4	14.5	18.1	–	16.9	17.6	20.2
Proximate, wt%									
Moisture	31.30	30.80	34.30	32.60	32.20	29.70	30.70	31.20	31.30
Volatile Matter	24.69	24.80	22.60	24.21	24.42	27.25	27.34	26.57	26.70
Fixed Carbon	40.01	41.00	38.70	38.46	38.93	38.63	38.05	37.74	37.49
Ash	4.00	3.40	4.40	4.73	4.45	4.41	3.92	4.49	4.51
Total	100.00	100.00	100.00	100.00	100.00	99.99	100.01	100.00	100.00
Ultimate, wt%									
Carbon	48.79	50.36	46.31	47.58	47.71	49.71	49.65	48.56	48.55
Hydrogen[b]	3.15	3.23	2.86	3.15	3.08	3.28	3.10	3.16	3.43
Oxygen in Fuel[b]	11.80	11.21	11.22	11.00	11.65	12.03	11.75	11.63	11.28
Nitrogen	0.63	0.69	0.61	0.61	0.62	0.59	0.60	0.59	0.61
Sulfur	0.32	0.31	0.30	0.33	0.29	0.27	0.28	0.36	0.32
Moisture	31.30	30.80	34.30	32.60	32.20	29.70	30.70	31.20	31.30
Ash	4.00	3.40	4.40	4.73	4.45	4.41	3.92	4.49	4.51
Total	99.99	100.00	100.00	100.00	100.00	99.99	100.00	99.99	100.00
Heating Value, Btu/lb	8157	8400	7682	7852	7997	8333	8254	8030	8058

[a] Does not include fluorine.

[b] Moisture not included in hydrogen and oxygen values.

Table A-5. Coal Analysis, as-received basis unless otherwise noted

Sample Date:	10/6/09	10/7/09	10/8/09	10/9/09	10/10/09	10/11/09	10/12/09	10/13/09	10/14/09
Sample Time:	1800–0600	1800–0600	1800–0600	1800–0600	1800–0600	1800–0600	1800–0600	1800–0600	1800–0600
Hg, ppm (dry)	0.0798	0.0798	0.0839	0.0747	0.0692	0.0686	0.0588	0.0696	0.0798
Halogens,[a] ppm (dry)	191.0	22.1	48.7	42.2	78.4	50.8	55.9	33.1	30.8
Proximate, wt%									
Moisture	29.40	31.30	32.70	30.90	31.70	33.30	32.70	27.00	31.10
Volatile Matter	27.48	26.57	25.17	26.45	26.21	24.33	24.85	25.58	24.92
Fixed Carbon	39.01	38.14	37.21	38.16	37.21	36.64	38.24	39.38	38.72
Ash	4.11	3.98	4.92	4.49	4.88	5.72	4.21	8.04	5.26
Total	100.00	99.99	100.00	100.00	100.00	99.99	100.00	100.00	100.00
Ultimate, wt%									
Carbon	50.74	49.02	46.95	48.84	48.20	45.68	47.28	49.03	47.79
Hydrogen[b]	3.47	3.40	3.14	3.37	3.21	2.99	3.19	3.29	3.00
Oxygen in Fuel[b]	11.39	11.44	11.34	11.51	11.15	11.48	11.78	11.76	11.92
Nitrogen	0.60	0.59	0.66	0.63	0.60	0.59	0.62	0.56	0.65
Sulfur	0.28	0.26	0.28	0.26	0.26	0.24	0.23	0.32	0.28
Moisture	29.40	31.30	32.70	30.90	31.70	33.30	32.70	27.00	31.10
Ash	4.11	3.98	4.92	4.49	4.88	5.72	4.21	8.04	5.26
Total	99.99	99.99	99.99	100.00	100.00	100.00	100.01	100.00	100.00
Heating Value, Btu/lb	8407	8132	7785	8194	8021	7610	7883	8272	7901

[a] Does not include fluorine.

[b] Moisture not included in hydrogen and oxygen values.

Table A-6. Coal Analysis, as-received basis unless otherwise noted

Sample Date:	10/15/09	10/16/09	10/17/09	10/18/09	10/19/09	10/20/09	10/21/09	10/22/09
Sample Time:	1800–0600	1800–0600	1800–0600	1800–0600	1800–0600	1800–0600	1800–0600	1800–0600
Hg, ppm (dry)	0.0540	0.0574	0.0703	0.0738	0.0643	0.0980	0.0773	0.0821
Halogens,[a] ppm (dry)	42.2	55.7	47.0	38.9	71.1	41.2	61.2	93.7
Proximate, wt%								
Moisture	32.60	33.50	32.20	33.90	28.80	26.20	32.60	31.00
Volatile Matter	25.01	24.60	24.59	25.01	25.28	25.31	25.09	26.44
Fixed Carbon	38.39	37.67	38.71	37.21	39.24	38.29	37.10	39.00
Ash	4.00	4.22	4.50	3.88	6.68	10.20	5.21	3.56
Total	100.00	99.99	100.00	100.00	100.00	100.00	100.00	100.00
Ultimate, wt%								
Carbon	48.06	47.01	47.57	46.88	48.53	47.02	46.59	50.01
Hydrogen[b]	3.19	2.89	2.97	3.02	3.24	3.07	2.99	3.16
Oxygen in Fuel[b]	11.11	11.36	11.73	11.47	11.86	12.60	11.77	11.40
Nitrogen	0.66	0.62	0.61	0.62	0.61	0.61	0.59	0.60
Sulfur	0.38	0.40	0.42	0.24	0.27	0.31	0.26	0.26
Moisture	32.60	33.50	32.20	33.90	28.80	26.20	32.60	31.00
Ash	4.00	4.22	4.50	3.88	6.68	10.20	5.21	3.56
Total	100.00	100.00	100.00	100.01	99.99	100.01	100.01	99.99
Heating Value, Btu/lb	7939	7802	7896	7841	8074	7895	7809	8347

[a] Does not include fluorine.

[b] Moisture not included in hydrogen and oxygen values.

APPENDIX B

CONTINUOUS MERCURY MONITOR DATA

CONTINUOUS MERCURY MONITOR DATA

For this project, three continuous mercury monitors (CMMs) were set up and operated by the EERC and plant personnel. The stack CMM was operated and maintained by plant personnel, and the Lodge inlet and ID fan outlet CMMs were located on the south side of the test unit and operated and maintained by EERC personnel. The monthly CMM data are presented in Figures B-1–B-3 for the entire test project. All of the CMM data is corrected to a µg/dNm^3 at 3% O$_2$ basis.

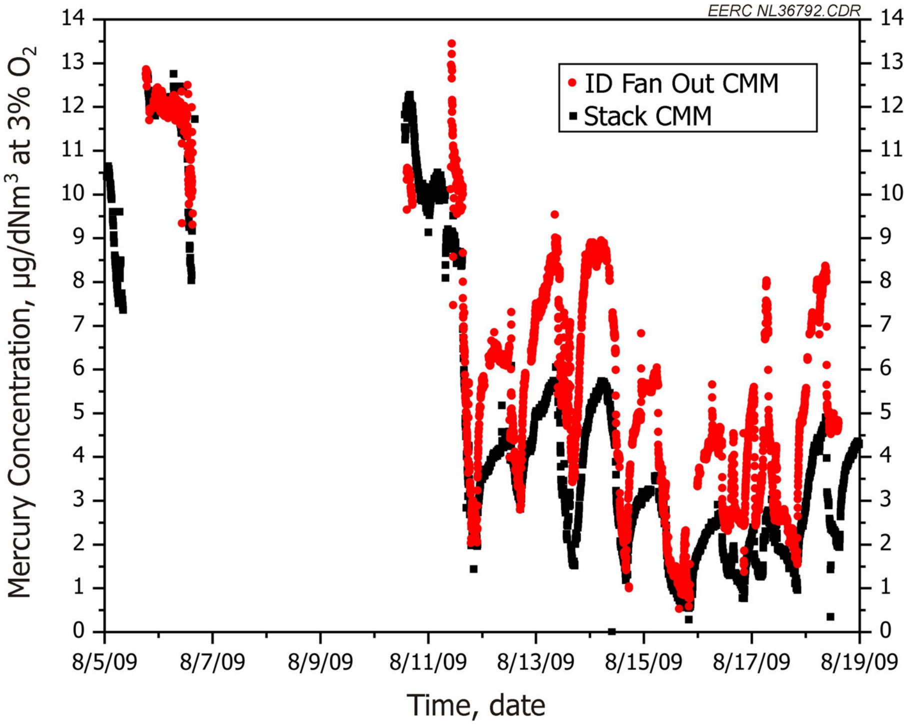


Figure B-1. August CMM data.

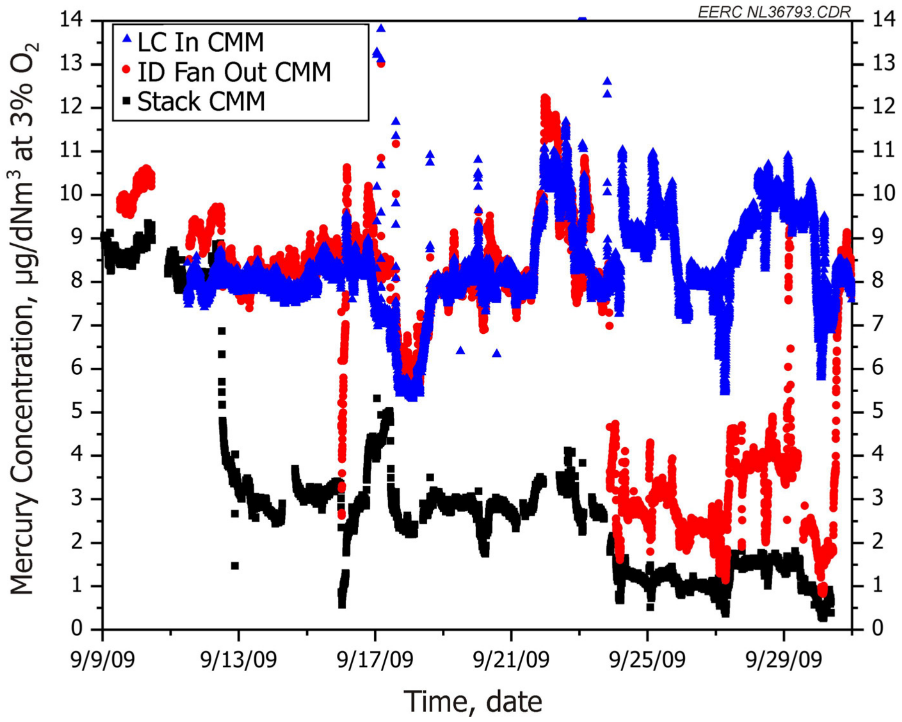


Figure B-2. September CMM data.

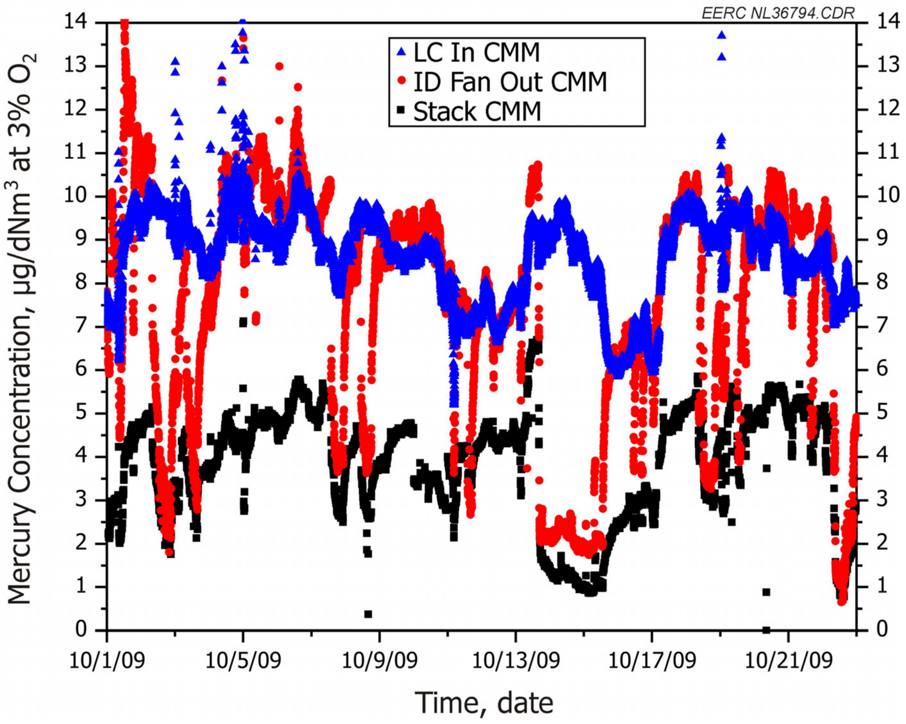


Figure B-3. October CMM data.

APPENDIX C

SORBENT TRAP DATA

SORBENT TRAP DATA

Over the course of the project, sorbent trap samples were taken at the Koppers (K) inlet, Lodge Cottrel (LC) inlet, induced draft (ID) fan outlet, and stack-sampling locations in order to provide mercury removal data across each pollution control device. Tables C-1–C-19 include the raw data from each of these samples.

Table C-1. Sorbent Trap Sample Data

Date:	8/6/2009	8/6/2009	8/6/2009	8/6/2009	8/11/2009	8/11/2009	8/11/2009	8/11/2009	8/11/2009
Start Time:	10:15	10:14	10:18	10:15	12:39	12:38	12:40	12:40	18:45
Stop Time:	11:07	11:14	11:18	11:15	13:38	13:38	13:40	13:40	19:35
Duration, min:	51.5	60	60	60	59	60	60	60	50
Location:	K In	LC In	ID Out	Stack	K In	LC In	ID Out	Stack	K In
Trap ID, No.:	53480	49871	53487	49696	54652	54681	54624	54686	53395
Vm, dL	27	36	33	51.4	31.6	31.0	31.7	51.1	26.5
Pb, in. Hg	29.64	29.64	29.64	29.64	29.88	29.88	29.88	29.88	29.84
Elevation corr, ft	60	140	0	400	60	140	0	400	60
Tm, °F	79	76.75	81.6	81.2	81.4	89.75	83	83	84.2
Cm	1.037	0.974	0.978	1.05	1.037	0.974	0.978	1.05	1.037
Moisture, %	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
O_2, %	3.56	5.58	6.46	6.46	3.17	4.85	5.63	5.61	3.16
Ash, ng	10	–	–	–	5.1	–	–	–	3.4
Plug 1, ng	8.5	8.3	4.2	40.0	1.8	3.0	0.2	7.1	1.1
Section 1, ng	343	393	346	429	271	234	236	348	201
Section 2 with Plug, ng	6.1	4.1	4.5	6.5	0.2	1.9	0.7	2.2	0.2
Back Plug, ng	0	0	0	0	0	0	0	0.0	0
Breakthrough, %	1.8	1.0	1.3	1.5	0.1	0.8	0.3	0.6	0.1
Vcorr, dNL	27.1	34.0	31.2	51.5	31.9	28.8	30.1	51.4	26.5
Hg, µg/dNm^3	13.56	11.92	11.38	9.24	8.73	8.29	7.87	6.95	7.75
Hg(O_2 corr), µg/dNm^3 at 3% O_2	13.99	13.92	14.09	11.44	8.81	9.24	9.22	8.13	7.82

Table C-2. Sorbent Trap Sample Data

Date:	8/11/2009	8/11/2009	8/11/2009	8/12/2009	8/12/2009	8/12/2009	8/12/2009	8/12/2009	8/12/2009
Start Time:	18:39	18:41	18:40	10:25	10:23	10:28	10:25	15:20	15:21
Stop Time:	19:39	19:41	19:40	11:24	11:23	11:28	11:25	16:20	16:21
Duration, min:	60	60	60	60	60	60	60	60	60
Location:	LC In	ID Out	Stack	K In	LC In	ID Out	Stack	K In	LC In
Trap ID, No.:	53426	53403	53481	49862	54576	53392	53479	54773	54724
Vm, dL	32.9	33.5	51.6	31.7	33.1	33.5	52.4	29.9	32.7
Pb, in. Hg	29.84	29.84	29.84	29.84	29.84	29.84	29.84	29.86	29.86
Elevation corr, ft	140	0	400	60	140	0	400	60	140
Tm, °F	90	84.6	84.6	72.6	85.75	76.8	84.6	84	94.24
Cm	0.974	0.978	1.05	1.037	0.974	0.978	1.05	1.037	0.974
Moisture, %	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
O_2, %	4.86	5.64	5.63	3.21	4.87	5.75	5.64	3.05	4.98
Ash, ng	–	–	–	1.3	–	–	–	3.1	–
Plug 1, ng	1.3	1.1	1.4	2.4	1.7	1.9	1.9	2.3	3.3
Section 1, ng	216	71	98	248	195	196	190	236	219
Section 2 with Plug, ng	0.8	1.4	0.6	0	0	0.5	0.5	0.6	0.6
Back Plug, ng	0	0	0	0	0	0	0	0	0
Breakthrough, %	0.4	2.0	0.6	0.0	0.0	0.3	0.3	0.3	0.3
Vcorr, dNL	30.5	31.7	51.7	32.4	31.0	32.1	52.5	30.0	30.1
Hg, µg/dNm^3	7.14	2.32	1.93	7.76	6.35	6.17	3.67	8.07	7.40
Hg(O_2 corr), µg/dNm^3 at 3% O_2	7.97	2.72	2.27	7.85	7.09	7.29	4.30	8.10	8.31

Table C-3. Sorbent Trap Sample Data

Date:	8/12/2009	8/12/2009	8/13/2009	8/13/2009	8/13/2009	8/13/2009	8/13/2009	8/13/2009	8/13/2009
Start Time	15:23	15:25	8:25	8:23	8:25	8:26	15:40	15:39	15:41
Stop Time:	16:23	16:25	9:25	9:23	9:25	9:26	16:40	16:39	16:41
Duration, min:	60	60	60	60	60	60	60	60	60
Location:	ID Out	Stack	K In	LC In	ID Out	Stack	K In	LC In	ID Out
Trap ID, No.:	54754	54735	54575	54774	54752	54751	54744	54722	54765
Vm, dL	33.2	51.0	32.2	32.2	32.8	52.9	32.8	32.1	33.7
Pb, in. Hg	29.86	29.86	29.90	29.90	29.90	29.90	29.87	29.87	29.87
Elevation corr, ft	0	400	60	140	0	400	60	140	0
Tm, °F	81.6	85.25	64.4	71.75	74.2	80.8	87.6	89.2	84
Cm	0.978	1.05	1.037	0.974	0.978	1.05	1.037	0.974	0.978
Moisture, %	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
O_2, %	5.75	5.76	3.05	4.99	5.79	5.78	3.01	5.37	6.22
Ash, ng	–	–	3.6	–	–	–	8.5	–	–
Plug 1, ng	1.4	3.4	2.1	3.7	2.3	3.6	5.7	7.8	1.3
Section 1, ng	104	133	339	282	271	233	217	169	112
Section 2 with Plug, ng	0	1.4	1.9	0.2	0.4	1.5	0.9	0.9	0.5
Back Plug, ng	0	0	0	0	0	0	0	0	0
Breakthrough, %	0.0	1.1	0.6	0.1	0.1	0.6	0.4	0.5	0.4
Vcorr, dNL	31.6	51.1	33.5	31.0	31.7	53.5	32.7	29.9	31.9
Hg, µg/dNm^3	3.34	2.70	10.34	9.23	8.64	4.45	7.10	5.95	3.56
Hg(O_2 corr), µg/dNm^3 at 3% O_2	3.94	3.19	10.37	10.38	10.22	5.27	7.11	6.85	4.34

Table C-4. Sorbent Trap Sample Data

Date:	8/13/2009	8/15/2009	8/15/2009	8/15/2009	8/15/2009	8/16/2009	8/16/2009	8/16/2009	8/16/2009
Start Time:	15:39	12:57	12:57	12:58	12:57	16:58	16:59	17:01	17:00
Stop Time:	16:39	13:57	13:57	13:58	13:57	17:58	17:59	18:01	18:00
Duration, min:	60	60	60	60	60	60	60	60	60
Location:	Stack	K In	LC In	ID Out	Stack	K In	LC In	ID Out	Stack
Trap ID, No.:	54708	54753	54746	54677	54726	54715	54721	54723	54770
Vm, dL	51.6	32.1	31.3	32.2	52.2	32.7	30.6	33.4	51.9
Pb, in. Hg	29.87	30.02	30.02	30.02	30.02	29.91	29.91	29.91	29.91
Elevation corr, ft	400	60	140	0	400	60	140	0	400
Tm, °F	82.6	76.2	74	80.2	79.8	85	98.4	87.6	83.2
Cm	1.05	1.037	0.974	0.978	1.05	1.037	0.974	0.978	1.05
Moisture, %	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
O_2, %	6.22	2.84	5.18	6.01	6.00	2.96	5.20	6.03	6.02
Ash, ng	–	5.1	–	–	–	10	–	–	–
Plug 1, ng	0.1	0.7	3.1	2.8	4.9	3.0	4.3	0.2	0.6
Section 1, ng	67	194	137	36	44.0	201	136.0	82	54.0
Section 2 with Plug, ng	1.1	0.5	1.4	1.8	0.2	0	0.9	0.7	2.0
Back Plug, ng	0	0	0	0	0.0	0	0.0	0	0.0
Breakthrough, %	1.6	0.3	1.0	5.0	0.5	0.0	0.7	0.9	3.7
Vcorr, dNL	51.9	32.8	30.1	30.9	53.1	32.8	28.0	31.5	52.2
Hg, µg/dNm^3	1.31	6.10	4.70	1.31	0.93	6.53	5.04	2.63	1.08
Hg(O_2 corr), µg/dNm^3 at 3% O_2	1.60	6.05	5.35	1.58	1.11	6.51	5.74	3.17	1.30

Table C-5. Sorbent Trap Sample Data

Date:	8/17/2009	8/17/2009	8/17/2009	8/17/2009	8/18/2009	8/18/2009	8/18/2009	8/18/2009	9/9/2009
Start Time:	15:45	14:32	14:34	14:32	12:15	12:16	12:18	12:15	13:12
Stop Time:	16:38	15:32	15:34	15:32	13:15	13:16	13:18	13:15	14:12
Duration, min:	53	60	60	60	60	60	60	60	60
Location:	K In	LC In	ID Out	Stack	K In	LC In	ID Out	Stack	K In
Trap ID, No.:	54743	54731	54707	54704	54829	54714	54781	54802	54742
Vm, dL	29.1	31.4	34.4	51.8	33.1	31.5	33.4	51.7	32.9
Pb, in. Hg	29.89	29.90	29.90	29.90	29.81	29.81	29.81	29.81	29.81
Elevation corr, ft	60	140	0	400	60	140	0	400	60
Tm, °F	104.2	102.6	91.8	88.4	88.2	99.8	89.2	91	83
Cm	1.037	0.974	0.978	1.05	1.037	0.974	0.978	1.05	1.037
Moisture, %	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
O_2, %	2.76	5.38	6.24	6.23	3.53	5.44	6.29	6.30	3.35
Ash, ng	10	–	–	–	12	–	–	–	5.9
Plug 1, ng	3.5	5.8	0.3	1.9	6.3	10.0	0.0	0.7	11.0
Section 1, ng	252.0	219.0	85.0	73.0	314.0	220.0	154.0	90.0	355.0
Section 2 with Plug, ng	0.6	1.8	1.9	0.8	0.0	0.0	1.5	0.0	0.3
Back Plug, ng	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Breakthrough, %	0.2	0.8	2.2	1.1	0.0	0.0	1.0	0.0	0.1
Vcorr, dNL	28.2	28.5	32.2	51.6	32.9	28.7	31.3	51.1	33.0
Hg, µg/dNm^3	9.45	7.94	2.71	1.47	10.11	8.01	4.97	1.77	11.28
Hg(O_2 corr), µg/dNm^3 at 3% O_2	9.33	9.15	3.31	1.79	10.42	9.27	6.08	2.17	11.51

Table C-6. Sorbent Trap Sample Data

Date:	9/9/2009	9/9/2009	9/9/2009	9/11/2009	9/11/2009	9/11/2009	9/11/2009	9/12/2009	9/12/2009
Start Time:	13:12	13:12	13:12	14:59	14:58	14:59	15:00	8:09	8:08
Stop Time:	14:12	14:12	14:12	15:42	15:58	15:59	16:00	8:42	9:08
Duration, min:	60	60	60	43	60	60	60	33	60
Location:	LC In	ID Out	Stack	K In	LC In	ID Out	Stack	K In	LC In
Trap ID, No.:	54675	54738	54740	54683	54689	54693	54699	54651	54653
Vm, dL	32.0	34.1	51.0	21.6	31.3	32.7	51.4	17.1	31.2
Pb, in. Hg	29.81	29.81	29.81	29.74	29.74	29.74	29.74	29.66	29.66
Elevation corr, ft	140	0	400	60	140	0	400	60	140
Tm, °F	85	83	83	96	104	89	87	70	78
Cm	0.974	0.978	1.05	1.037	0.974	0.978	1.05	1.037	0.974
Moisture, %	0.0	12.5	0.0	0.0	12.5	12.0	0.0	12.5	12.0
O_2, %	5.21	6.02	6.03	3.11	5.22	6.02	6.04	3.97	5.65
Ash, ng	–	–	–	0	–	–	–	0	–
Plug 1, ng	2.8	21.0	30.0	12.0	2.9	8.5	43.0	5.6	10.0
Section 1, ng	299.0	285.0	344.0	188.0	235.0	254.0	293.0	162.0	261.0
Section 2 with Plug, ng	0.9	0.2	0.0	0.5	3.0	0.1	1.6	0.9	0.9
Back Plug, ng	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Breakthrough, %	0.3	0.1	0.0	0.3	1.3	0.0	0.5	0.6	0.3
Vcorr, dNL	29.9	32.3	51.2	21.1	28.2	30.6	51.1	17.5	29.4
Hg, µg/dNm^3	10.11	9.48	7.31	9.50	8.53	8.59	6.61	9.64	9.24
Hg(O_2 corr), µg/dNm^3 at 3% O_2	11.52	11.39	8.79	9.56	9.73	10.32	7.95	10.19	10.84

Table C-7. Sorbent Trap Sample Data

Date:	9/12/2009	9/12/2009	9/12/2009	9/12/2009	9/12/2009	9/12/2009	9/13/2009	9/13/2009	9/13/2009
Start Time:	8:09	8:13	13:08	13:08	13:09	13:09	10:12	10:12	10:12
Stop Time:	9:09	9:13	14:01	14:08	14:09	14:08	10:56	11:12	11:12
Duration, min:	60	60	53.25	60	60	60	55.5	60	60
Location:	ID Out	Stack	K In	LC In	ID Out	Stack	K In	LC In	ID Out
Trap ID, No.:	54602	54649	54601	54739	54775	54747	54872	54719	54727
Vm, dL	32.7	51.4	28.3	23.6	33.1	52.4	30.0	31.7	33.0
Pb, in. Hg	29.66	29.66	29.57	29.57	29.57	29.57	29.44	29.44	29.44
Elevation corr, ft	0	400	60	140	0	400	60	140	0
Tm, °F	70	88	103	101	89	89	82	83	78
Cm	0.978	1.05	1.037	0.974	0.978	1.05	1.037	0.974	0.978
Moisture, %	12.0	20.0	12.5	12.0	12.0	20.0	6.0	12.5	12.0
O_2, %	6.52	6.54	3.85	5.54	6.39	6.41	4.03	5.63	6.49
Ash, ng	–	–	0	–	–	–	0	–	–
Plug 1, ng	7.1	8.9	38.0	8.7	14.0	4.9	10.0	10.0	53.0
Section 1, ng	252.0	345.0	215.0	223.0	213.0	169.0	270.0	226.0	188.0
Section 2 with Plug, ng	1.0	0.1	0.4	0.3	0.5	1.2	0.6	0.8	0.8
Back Plug, ng	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Breakthrough, %	0.4	0.0	0.2	0.1	0.2	0.7	0.2	0.4	0.4
Vcorr, dNL	31.6	50.9	27.1	21.3	30.8	51.6	29.8	29.4	31.2
Hg, $\mu g/dNm^3$	8.24	6.96	9.33	10.90	7.39	3.39	9.43	8.05	7.76
Hg(O_2 corr), $\mu g/dNm^3$ at 3% O_2	10.24	8.67	9.80	12.69	9.11	4.19	10.00	9.43	9.62

Table C-8. Sorbent Trap Sample Data

Date:	9/13/2009	9/14/2009	9/14/2009	9/14/2009	9/14/2009	9/15/2009	9/15/2009	9/15/2009	9/15/2009
Start Time:	10:12	8:28	8:26	8:28	8:26	9:15	8:55	8:57	8:58
Stop Time:	11:12	9:01	9:26	9:28	9:26	9:40	9:55	9:57	9:58
Duration, min:	60	33	60	60	60	25.25	60	60	60
Location:	Stack	K In	LC In	ID Out	Stack	K In	LC In	ID Out	Stack
Trap ID, No.:	54717	54801	54718	54832	54776	54777	54865	54732	54863
Vm, dL	52.4	17.9	32.0	32.5	52.0	13.4	31.8	33.1	52.0
Pb, in. Hg	29.44	29.70	29.70	29.70	29.70	29.92	29.92	29.92	29.92
Elevation corr, ft	400	60	140	0	400	60	140	0	400
Tm, °F	87	67	75	77	82	75	85	76	86
Cm	1.05	1.037	0.974	0.978	1.05	1.037	0.974	0.978	1.05
Moisture, %	20.0	6.0	12.5	12.0	20.0	6.0	12.5	12.0	20.0
O_2, %	6.51	3.84	5.65	6.52	6.54	4.47	5.55	6.43	6.42
Ash, ng	–	0	–	–	–	0	–	–	–
Plug 1, ng	2.3	4.7	12.0	1.3	24.0	9.0	10.0	0.2	2.0
Section 1, ng	124.0	168.0	238.0	219.0	936.0	141.0	283.0	275.0	142.0
Section 2 with Plug, ng	0.9	0.0	0.3	0.3	1.0	0.3	0.2	0.7	0.1
Back Plug, ng	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Breakthrough, %	0.7	0.0	0.1	0.1	0.1	0.2	0.1	0.3	0.1
Vcorr, dNL	51.5	18.4	30.4	31.0	52.1	13.7	29.9	31.9	52.1
Hg, µg/dNm^3	2.47	9.37	8.24	7.11	18.45	10.98	9.82	8.65	2.77
Hg(O_2 corr), µg/dNm^3 at 3% O_2	3.07	9.83	9.66	8.84	22.97	11.96	11.44	10.69	3.41

Table C-9. Sorbent Trap Sample Data

Date:	9/16/2009	9/16/2009	9/16/2009	9/16/2009	9/17/2009	9/17/2009	9/17/2009	9/17/2009	9/18/2009
Start Time:	13:17	13:01	13:02	13:02	17:55	17:36	17:37	17:36	14:00
Stop Time:	14:05	14:01	14:02	14:02	18:25	18:36	18:37	18:36	15:00
Duration, min:	58	60	60	60	30	60	60	60	60
Location:	K In	LC In	ID Out	Stack	K In	LC In	ID Out	Stack	K In
Trap ID, No.:	54874	54868	54772	54871	54862	54869	54833	54830	54827
Vm, dL	31.5	32.2	31.9	51.4	16.3	33.1	33.3	52.0	32.3
Pb, in. Hg	29.87	29.87	29.87	29.87	29.93	29.93	29.93	29.93	29.67
Elevation corr, ft	60	140	0	400	60	140	0	400	60
Tm, °F	81.2	84.8	83.8	86	81.75	96.2	82.6	86.4	92.4
Cm	1.037	0.974	0.978	1.05	1.037	0.974	0.978	1.05	1.037
Moisture, %	6.0	12.5	12.0	20.0	6.0	12.5	12.0	20.0	6.0
O_2, %	4.71	5.60	6.50	6.48	5.30	6.23	7.21	7.21	4.71
Ash, ng	9.1	–	–	–	1.6	–	–	–	6.0
Plug 1, ng	2.5	10.0	2.5	0.2	1.5	3.7	0.3	2.0	4.5
Section 1, ng	347	264.0	233	117	115	180	173	103	265.0
Section 2 with Plug, ng	1.2	0.0	0	0	0	0.9	0.3	0.9	0.3
Back Plug, ng	0	0.0	0	0	0	0	0	0	0.0
Breakthrough, %	0.3	0.0	0.0	0.0	0.0	0.5	0.2	0.9	0.1
Vcorr, dNL	31.8	30.2	30.2	51.4	16.4	30.5	31.7	52.1	31.7
Hg, µg/dNm^3	11.33	9.07	7.79	2.28	7.18	6.06	5.48	2.03	8.70
Hg(O_2 corr), µg/dNm^3 at 3% O_2	12.52	10.60	9.67	2.83	8.23	7.38	7.15	2.65	9.62

Table C-10. Sorbent Trap Sample Data

Date:	9/18/2009	9/18/2009	9/18/2009	9/19/2009	9/19/2009	9/19/2009	9/19/2009	9/20/2009	9/20/2009
Start Time:	13:50	13:51	13:51	13:15	13:05	13:06	13:06	12:10	12:08
Stop Time:	14:50	14:51	14:51	14:15	14:05	14:06	14:06	13:10	13:08
Duration, min:	60	60	60	60	60	60	60	60	60
Location:	LC In	ID Out	Stack	K In	LC In	ID Out	Stack	K In	LC In
Trap ID, No.:	54811	54867	54861	54736	54778	54875	54804	54826	54866
Vm, dL	31.8	33.4	52.6	32.4	31.1	33.0	52.2	33.0	31.9
Pb, in. Hg	29.67	29.67	29.67	29.83	29.83	29.83	29.83	30.20	30.20
Elevation corr, ft	140	0	400	60	140	0	400	60	140
Tm, °F	101.4	84	87.2	80.2	79.2	80.2	85.6	74	86.4
Cm	0.974	0.978	1.05	1.037	0.974	0.978	1.05	1.037	0.974
Moisture, %	12.5	12	20	6.0	12.5	12	20	6.0	12.5
O_2, %	5.54	6.40	6.41	4.50	5.59	6.44	6.47	4.67	5.65
Ash, ng	–	–	–	15	–	–	–	10	–
Plug 1, ng	4.4	1.0	0.5	1.8	5.1	1.3	0.9	0.9	7.5
Section 1, ng	217	212	122	305	249	233	122	338	245
Section 2 with Plug, ng	0.8	0.6	1.6	0	0.1	0.5	0.3	0.7	0
Back Plug, ng	0	0	0	0	0	0	0	0	0
Breakthrough, %	0.4	0.3	1.3	0.0	0.0	0.2	0.2	0.2	0.0
Vcorr, dNL	28.8	31.4	52.1	32.7	29.4	31.5	52.2	34.1	30.2
Hg, µg/dNm^3	7.73	6.79	2.38	9.85	8.64	7.47	2.36	10.26	8.37
Hg(O_2 corr), µg/dNm^3 at 3% O_2	9.00	8.38	2.94	10.74	10.09	9.23	2.93	11.31	9.82

Table C-11. Sorbent Trap Sample Data

Date:	9/20/2009	9/20/2009	9/21/2009	9/21/2009	9/21/2009	9/21/2009	9/22/2009	9/22/2009	9/22/2009
Start Time:	12:10	12:10	12:21	14:13	14:13	12:21	13:36	16:24	16:25
Stop Time:	13:10	13:10	13:21	15:13	15:13	13:21	14:36	17:24	17:25
Duration, min:	60	60	60	60	60	60	60	60	60
Location:	ID Out	Stack	K In	LC In	ID Out	Stack	K In	LC In	ID Out
Trap ID, No.:	54684	54695	54828	54846	54870	54873	54803	54805	54700
Vm, dL	32.6	51.8	32.9	32.7	32.8	52.4	32.1	34.4	32.8
Pb, in. Hg	30.20	30.20	30.04	30.00	30.00	30.04	29.83	29.78	29.78
Elevation corr, ft	0	400	60	140	0	400	60	140	0
Tm, °F	73.6	84	78.4	98.4	82	84.6	95.4	114.8	89.8
Cm	0.978	1.05	1.037	0.974	0.978	1.05	1.037	0.974	0.978
Moisture, %	12	20	6.0	12.5	12	20	6.0	12.5	12
O_2, %	6.54	6.54	4.36	5.41	6.29	6.26	4.31	5.48	6.26
Ash, ng	–	–	10	–	–	–	5.8	–	–
Plug 1, ng	0.7	1.8	2.5	7.4	0.9	1.9	0.4	6.0	4.4
Section 1, ng	252	123	296	242	231	128	385	292	271
Section 2 with Plug, ng	0	0	0.9	1.3	1.1	1.2	0.4	1.1	1.1
Back Plug, ng	0	0	0	0	0	0	0	0	0
Breakthrough, %	0.0	0.0	0.3	0.5	0.5	0.9	0.1	0.4	0.4
Vcorr, dNL	31.8	52.6	33.5	30.1	31.3	52.8	31.5	30.5	30.7
Hg, µg/dNm^3	7.94	2.37	9.23	8.34	7.44	2.48	12.44	9.81	9.02
Hg(O_2 corr), µg/dNm^3 at 3% O_2	9.88	2.95	9.98	9.63	9.10	3.03	13.41	11.38	11.01

Table C-12. Sorbent Trap Sample Data

Date:	9/22/2009	9/23/2009	9/23/2009	9/23/2009	9/23/2009	9/24/2009	9/24/2009	9/24/2009	9/24/2009
Start Time:	13:37	13:20	15:32	15:32	13:21	10:40	12:22	12:22	10:40
Stop Time:	14:37	14:20	16:32	16:32	14:21	11:40	13:22	13:22	11:40
Duration, min:	60	60	60	60	60	60	60	60	60
Location:	Stack	K In	LC In	ID Out	Stack	K In	LC In	ID Out	Stack
Trap ID, No.:	54831	54734	54771	54741	54745	54691	54690	54696	54680
Vm, dL	52.6	31.9	32.6	31.8	52.8	32.9	31.9	32.5	53.1
Pb, in. Hg	29.83	29.81	29.81	29.81	29.81	30.00	30.00	30.00	30.00
Elevation corr, ft	400	60	140	0	400	60	140	0	400
Tm, °F	87.2	92	103	89.6	91	75	78.6	76.4	88.6
Cm	1.05	1.037	0.974	0.978	1.05	1.037	0.974	0.978	1.05
Moisture, %	20	6.0	12.5	12	20	6.0	12.5	12	20
O_2, %	6.34	4.31	5.50	6.42	6.36	4.45	5.50	6.30	6.37
Ash, ng	–	4.9	–	–	–	6.9	–	–	–
Plug 1, ng	12	1.8	8.3	0.7	18	3.1	10	1.8	4.3
Section 1, ng	172	305	231	211	128	354	268	73	64
Section 2 with Plug, ng	0.7	0.7	0.8	0.2	0	1.8	0.8	1.7	1.5
Back Plug, ng	0	0	0	0	0	0	0	0	
Breakthrough, %	0.4	0.2	0.3	0.1	0.0	0.5	0.3	2.3	2.3
Vcorr, dNL	52.4	31.5	29.5	29.8	52.2	33.7	30.4	31.4	53.1
Hg, µg/dNm^3	3.52	9.93	8.13	7.12	2.80	10.86	9.17	2.44	1.31
Hg(O_2 corr), µg/dNm^3 at 3% O_2	4.33	10.71	9.44	8.79	3.44	11.81	10.65	2.99	1.62

Table C-13. Sorbent Trap Sample Data

Date:	9/25/2009	9/25/2009	9/25/2009	9/25/2009	9/25/2009	9/25/2009	9/26/2009	9/26/2009	9/26/2009
Start Time:	10:08	12:19	12:20	10:08	16:12	16:12	9:36	9:37	9:36
Stop Time:	11:08	13:19	13:20	11:08	17:09	17:08	10:36	10:37	10:36
Duration, min:	60	60	60	60	57	54	60	60	60
Location:	K In	Lc In	ID Out	Stack	K In	ID Out	K In	LC In	ID Out
Trap ID, No.:	49840	49834	54600	49806	49809	49826	49688	49700	49863
Vm, dL	31.3	32.9	33.9	52.9	31.0	28.6	32.3	30.4	33.0
Pb, in. Hg	30.03	30.01	30.01	30.03	29.98	29.98	30.10	30.10	30.10
Elevation corr, ft	60	140	0	400	60	0	60	140	0
Tm, °F	74	88.2	76	83.4	81.75	83.4	65	74.4	69.6
Cm	1.037	0.974	0.978	1.05	1.037	0.978	1.037	0.974	0.978
Moisture, %	6.0	12.5	12	20	6.0	12	6.0	12.5	12
O_2, %	4.33	5.25	6.06	6.07	4.30	5.30	4.71	5.66	6.55
Ash, ng	8.2	–	–	–	13	–	3.9	–	–
Plug 1, ng	2.1	4	1.7	4.9	0	1.1	1.8	51	1.9
Section 1, ng	347	300	84	66	347	75	283	181	64
Section 2 with Plug, ng	0.4	0.9	1.7	0.2	0.6	0	0	0.1	1.2
Back Plug, ng	0	0	0	0	0	0	0	0	0
Breakthrough, %	0.1	0.3	2.0	0.3	0.2	0.0	0.0	0.1	1.9
Vcorr, dNL	32.1	30.8	32.8	53.4	31.3	27.2	33.8	29.3	32.4
Hg, μg/dNm^3	11.13	9.90	2.67	1.33	11.51	2.79	8.54	7.92	2.07
Hg(O_2 corr), μg/dNm^3 at 3% O_2	12.01	11.31	3.21	1.60	12.41	3.20	9.43	9.30	2.58

Table C-14. Sorbent Trap Sample Data

Date:	9/26/2009	9/27/2009	9/27/2009	9/27/2009	9/27/2009	9/28/2009	9/28/2009	9/28/2009	9/28/2009
Start Time:	9:37	12:26	12:27	12:28	12:28	9:25	9:23	9:25	9:24
Stop Time:	10:37	13:26	13:27	13:28	13:28	10:25	10:23	10:25	10:24
Duration, min:	60	60	60	60	60	60	60	60	60
Location:	Stack	K In	LC In	ID Out	Stack	K In	LC In	ID Out	Stack
Trap ID, No.:	49784	49717	49867	53429	49777	49690	49779	49788	49831
Vm, dL	52.7	32.3	32.1	33.7	55.8	32.0	30.1	34.2	53.4
Pb, in. Hg	30.10	29.92	29.92	29.92	29.92	29.54	29.54	29.54	29.54
Elevation corr, ft	400	60	140	0	400	60	140	0	400
Tm, °F	84.4	69.6	84.2	75.4	80	64.2	67.2	68	76.4
Cm	1.05	1.037	0.974	0.978	1.05	1.037	0.974	0.978	1.05
Moisture, %	20	6.0	12.5	12	20	6.0	12.5	12	20
O_2, %	6.55	4.28	5.32	6.16	6.16	4.79	5.79	6.61	6.70
Ash, ng	–	4.6	–	–	–	6.9	–	–	–
Plug 1, ng	5	2.6	2.8	0.4	1.4	5.9	34	0.2	0
Section 1, ng	56	332	279	124	82	351	257	102	75
Section 2 with Plug, ng	1.5	0.5	0	0	0	0	1.2	0	0
Back Plug, ng	0	0	0	0	0	0	0	0	0
Breakthrough, %	2.7	0.2	0.0	0.0	0.0	0.0	0.5	0.0	0.0
Vcorr, dNL	53.3	33.3	30.2	32.5	56.5	32.9	28.9	33.0	53.8
Hg, µg/dNm^3	1.17	10.19	9.33	3.83	1.48	11.05	10.13	3.09	1.40
Hg(O_2 corr), µg/dNm^3 at 3% O_2	1.46	10.97	10.71	4.64	1.79	12.27	11.99	3.87	1.76

Table C-15. Sorbent Trap Sample Data

Date:	9/29/2009	9/29/2009	9/29/2009	9/29/2009	9/30/2009	9/30/2009	9/30/2009	9/30/2009	10/2/2009
Start Time:	8:24	8:25	8:26	8:25	8:20	8:21	8:20	8:22	15:30
Stop Time:	9:24	9:25	9:26	9:25	8:37	9:21	9:20	9:22	16:30
Duration, min:	60	60	60	60	17	60	60	60	60
Location:	K In	LC In	ID Out	Stack	K In	LC In	ID Out	Stack	K In
Trap ID, No.:	49849	49824	49803	49830	49869	49835	53471	49783	49829
Vm, dL	32.2	28.8	34.3	54.2	8.5	29.9	34.2	52.3	34.5
Pb, in. Hg	29.66	29.66	29.66	29.66	30.01	30.01	30.01	30.01	29.90
Elevation corr, ft	60	140	0	400	60	140	0	400	60
Tm, °F	56.2	61	64.4	72.2	54.7	64	65.4	75	75.2
Cm	1.037	0.974	0.978	1.05	1.037	0.974	0.978	1.05	1.037
Moisture, %	6.0	12.5	12	20	6.0	12.5	12	20	6.0
O_2, %	4.53	5.56	6.41	6.43	4.74	5.73	6.61	6.63	4.77
Ash, ng	5.6	–	–	–	1.6	–	–	–	1.8
Plug 1, ng	1.4	6.4	0.2	21	0	3.7	0.8	5.6	0
Section 1, ng	374	287	109	108	75	203	49	40	361
Section 2 with Plug, ng	0	0	0.3	0	0.5	0	0	1.2	0.9
Back Plug, ng	0	0	0	0	0	0	0	0	0
Breakthrough, %	0.0	0.0	0.3	0.0	0.7	0.0	0.0	3.0	0.2
Vcorr, dNL	33.8	28.0	33.5	55.2	9.1	29.3	33.7	53.6	35.2
Hg, µg/dNm^3	11.28	10.46	3.27	2.34	8.52	7.06	1.48	0.87	10.33
Hg(O_2 corr), µg/dNm^3 at 3% O_2	12.32	12.20	4.03	2.89	9.43	8.32	1.85	1.09	11.46

Table C-16. Sorbent Trap Sample Data

Date:	10/2/2009	10/2/2009	10/2/2009	10/3/2009	10/3/2009	10/3/2009	10/3/2009	10/5/2009	10/5/2009
Start Time:	15:27	15:28	15:28	13:02	12:58	13:00	13:01	10:28	10:25
Stop Time:	16:27	16:28	16:28	14:02	13:58	14:00	14:01	11:28	11:25
Duration, min:	60	60	60	60	60	60	60	60	60
Location:	LC In	ID Out	Stack	K In	LC In	ID Out	Stack	K In	LC In
Trap ID, No.:	49785	49810	49781	49833	53498	49786	49780	49872	49866
Vm, dL	31.4	33.5	53.0	34.0	30.8	34.0	54.6	33.5	31.5
Pb, in. Hg	29.90	29.90	29.90	29.78	29.78	29.78	29.78	29.94	29.94
Elevation corr, ft	140	0	400	60	140	0	400	60	140
Tm, °F	80.4	75.4	77.4	59.2	71.4	66.4	75.4	66.2	69.2
Cm	0.974	0.978	1.05	1.037	0.974	0.978	1.05	1.037	0.974
Moisture, %	12.5	12	20	6.0	12.5	12	20	6.0	12.5
O_2, %	5.69	6.59	6.58	4.88	5.88	6.84	6.81	4.69	5.91
Ash, ng	–	–	–	2.5	–	–	–	6.7	–
Plug 1, ng	1.7	1.4	6.6	0	0	0.7	3.3	0.1	3.3
Section 1, ng	278	91	115	374	280	104	141	364	293
Section 2 with Plug, ng	0	0	0	0	0.9	0	0	0.2	0
Back Plug, ng	0	0	0	0	0	0	0	0	0
Breakthrough, %	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.1	0.0
Vcorr, dNL	29.7	32.3	53.9	35.6	29.5	33.2	55.5	34.8	30.5
Hg, µg/dNm^3	9.41	2.86	2.26	10.57	9.51	3.15	2.60	10.66	9.72
Hg(O_2 corr), µg/dNm^3 at 3% O_2	11.06	3.57	2.82	11.80	11.32	4.01	3.30	11.76	11.59

Table C-17. Sorbent Trap Sample Data

Date:	10/5/2009	10/5/2009	10/5/2009	10/5/2009	10/5/2009	10/5/2009	10/6/2009	10/6/2009	10/6/2009
Start Time:	10:24	10:27	14:05	14:03	14:05	14:06	8:50	8:47	8:45
Stop Time:	11:24	11:27	15:05	15:03	15:05	14:06	9:50	9:47	9:45
Duration, min:	60	60	60	60	60	60	60	60	60
Location:	ID Out	Stack	K In	LC In	ID Out	Stack	K In	LC In	ID Out
Trap ID, No.:	53269	53379	49801	49691	49808	49828	49782	53457	53432
Vm, dL	33.2	56.6	34.6	31.2	33.2	54.3	34.2	28.2	33.2
Pb, in. Hg	29.94	29.94	29.94	29.94	29.94	29.94	30.04	30.04	30.04
Elevation corr, ft	0	400	60	140	0	400	60	140	0
Tm, °F	61.4	77	76.4	91	75.8	78.6	54.4	60	57.2
Cm	0.978	1.05	1.037	0.974	0.978	1.05	1.037	0.974	0.978
Moisture, %	12	20	6.0	12.5	12	20	6.0	12.5	12
O_2, %	6.84	6.84	4.63	5.88	6.81	6.81	4.47	5.76	6.65
Ash, ng	–	–	2.8	–	–	–	3.6	–	–
Plug 1, ng	0	0.6	0	12	0	14	3	0.9	0
Section 1, ng	320	280	388	287	327	285	417	278	303
Section 2 with Plug, ng	0	0	0.1	0.7	0	0	0.5	0.5	0.6
Back Plug, ng	0	0	0	0	0	0	0	0	0
Breakthrough, %	0.0	0.0	0.0	0.2	0.0	0.0	0.1	0.2	0.2
Vcorr, dNL	32.9	57.7	35.3	29.0	32.0	55.2	36.5	27.9	33.3
Hg, µg/dNm^3	9.73	4.86	11.08	10.33	10.21	5.42	11.63	10.02	9.12
Hg(O_2 corr), µg/dNm^3 at 3% O_2	12.36	6.18	12.19	12.30	12.96	6.87	12.66	11.84	11.44

Table C-18. Sorbent Trap Sample Data

Date:	10/6/2009	10/8/2009	10/8/2009	10/8/2009	10/8/2009	10/14/2009	10/14/2009	10/14/2009	10/14/2009
Start Time:	8:47	16:50	16:47	16:47	16:48	8:31	10:22	8:31	8:32
Stop Time:	9:47	17:50	17:47	17:47	17:48	9:31	11:22	9:31	9:32
Duration, min:	60	60	60	60	60	60	60	60	60
Location:	Stack	K In	LC In	ID Out	Stack	K In	LC In	ID Out	Stack
Trap ID, No.:	53378	49789	49804	49787	49802	49734	49805	49776	53455
Vm, dL	53.3	31.8	30.6	33.1	52.8	31.2	30.4	33.9	54.2
Pb, in. Hg	30.04	29.92	29.92	29.92	29.92	29.16	29.16	29.16	29.16
Elevation corr, ft	400	60	140	0	400	60	140	0	400
Tm, °F	78.4	79.6	90.4	78.8	80.6	64	69	69.4	73
Cm	1.05	1.037	0.974	0.978	1.05	1.037	0.974	0.978	1.05
Moisture, %	20	6.0	12.5	12	20	6.0	12.5	12	20
O_2, %	6.67	3.60	4.86	5.61	5.63	2.79	5.16	5.97	5.97
Ash, ng	–	12	–	–	–	8	–	–	–
Plug 1, ng	15	0.5	1.9	0.2	5.9	4.3	5.8	2.9	16
Section 1, ng	253	374	287	113	169	354	290	75	103
Section 2 with Plug, ng	0	0.5	0	0	0	2.4	0.5	0	0.3
Back Plug, ng	0	0	0	0	0	0	0	0	0
Breakthrough, %	0.0	0.1	0.0	0.0	0.0	0.7	0.2	0.0	0.3
Vcorr, dNL	54.4	32.2	28.5	31.7	53.4	31.7	28.7	32.2	54.2
Hg, µg/dNm^3	4.93	12.02	10.15	3.57	3.27	11.63	10.34	2.42	2.20
Hg(O_2 corr), µg/dNm^3 at 3% O_2	6.19	12.43	11.32	4.17	3.83	11.49	11.75	2.89	2.64

Table C-19. Sorbent Trap Sample Data

Date:	10/15/2009	10/15/2009	10/15/2009	10/15/2009	10/18/2009	10/18/2009	10/18/2009	10/18/2009
Start Time:	10:13	11:51	10:13	11:53	15:46	14:12	15:48	14:13
Stop Time:	11:13	12:51	11:13	12:53	16:46	15:12	16:48	15:13
Duration, min:	60	60	60	60	60	60	60	60
Location:	K In	LC In	ID Out	Stack	K In	LC In	ID Out	Stack
Trap ID, No.:	53428	53483	49861	49714	53477	53482	53456	53451
Vm, dL	30.9	31.6	33.9	53.4	32.6	30.8	35.0	54.0
Pb, in. Hg	29.93	29.93	29.93	29.93	29.72	29.74	29.72	29.74
Elevation corr, ft	60	140	0	400	60	140	0	400
Tm, °F	64.4	75	68.2	76.2	74.2	80	77.2	79.6
Cm	1.037	0.974	0.978	1.05	1.037	0.974	0.978	1.05
Moisture, %	6.0	12.5	12	20	6.0	12.5	12	20
O_2, %	2.84	5.03	5.87	5.82	2.68	4.98	5.77	5.76
Ash, ng	6.7	–	–	–	3.3	–	–	–
Plug 1, ng	3.9	4.9	0	11	0	0	0.2	0.1
Section 1, ng	322	275	83	78	345	279	116	178
Section 2 with Plug, ng	0	0.1	0	1.1	0.7	0.3	1	0.2
Back Plug, ng	0	0	0	0	0	0	0	0
Breakthrough, %	0.0	0.0	0.0	1.4	0.2	0.1	0.9	0.1
Vcorr, dNL	32.2	30.2	33.2	54.5	33.1	29.0	33.4	54.4
Hg, µg/dNm^3	10.33	9.26	2.50	1.65	10.54	9.62	3.51	3.28
Hg(O_2 corr), µg/dNm^3 at 3% O_2	10.24	10.43	2.98	1.96	10.35	10.81	4.14	3.87

APPENDIX D

SAMPLE CALCULATIONS

SAMPLE CALCULATIONS

Mercury Concentrations Corrected to a Dry Flue Gas Basis

Hg ($\mu g/m^3$) = uncorrected wet mercury concentration

Hg ($\mu g/dm^3$) = uncorrected dry mercury concentration

m^3 = wet flue gas volume

dm^3 = dry flue gas volume

$\mu g/m^3 \times (m^3/dm^3) = \mu g/dm^3$

The data used in the sample calculation below are from the stack continuous mercury monitor (CMM) value on 9/26/2009 at 11:45 and an average stack moisture value of 21.3%:

$0.657\ \mu g/m^3 \times (1\ m^3/(1 - 0.213)dm^3) = 0.835\ \mu g/dm^3$

Raw CMM Values to Corrected CMM Values

Hg ($\mu g/m^3$) = uncorrected mercury concentration in the flue gas

Hg ($\mu g/dNm^3$ at 3% O_2) = mercury concentration in the flue gas corrected to standard conditions

d = dry (moisture contribution is removed from the flue gas)

O_2 = percent O_2 measured at sampling location

Hg ($\mu g/dNm^3$ at 3% O_2) = Hg ($\mu g/m^3$) × $18/(21 - O_2)$

The data used in the sample calculation below are from the stack CMM value on 9/26/2009 at 11:45 and an average stack moisture value of 21.3%:

Hg ($\mu g/dNm^3$ at 3% O_2) = $0.657 \times 18/(21 - 6.56) \times 1.271 = 1.04$ $\mu g/dNm^3$ at 3% O_2

Flue Gas Hg Concentration from Sorbent Trap (ST) Samples

Hg ($\mu g/dNm^3$ at 3% O_2) = mercury concentration in the flue gas corrected to standard conditions

Hg ($\mu g/dNm^3$ at 3% O_2) = $(F + S1 + S2) \div Vcorr \times 18/(21 - O_2)$

Vcorr (dNL) = volume sampled corrected to standard conditions

Vcorr (dNL) = $Vm \times Cm \times (Pb - Elev\ corr/1000) \div 29.92 \times 528 \div (460 + Tm)$

The data used in the sample calculation below are from the stack ST collected on 8/6/2009 at 10:15:

V_{corr} (dNL) = 51.4 × 1.05 × (29.64 − 400/1000) ÷ 29.92 × 528 ÷ (460 + 81) = 51.5 dNL

Hg (μg/dNm^3 at 3%O_2) = (40.0 + 429 + 6.5) ÷ 51.5 × 18/(21 – 6.46) = 11.4 μg/dNm^3 at 3%O_2

Where:
Vm = volume of gas sample measured by the dry gas meter (dL)
Pb = barometric pressure (in Hg)
Elev corr = elevation correction for Pb to sampling elevation (ft)
Tm = meter temperature (°F)
Cm = meter correction factor (unitless, via calibration)
O_2 = flue gas O_2 concentration measured (%)
F = measured mass of Hg in front wool + plug (ng)
S1 = measured mass of Hg in Section 1 (ng)
S2 = measured mass of Hg in Section 2 and plug (ng)

Hg Removal

Hg_{Out} = Hg (μg/dNm^3 at 3% O_2) mercury concentration at the outlet location

Hg_{In} = Hg (μg/dNm^3 at 3% O_2) ST mercury concentration at the inlet location

% Hg Removal = the percent of mercury removed from the flue gas based on the inlet and outlet mercury concentrations

% Hg Removal = 100 – (Hg_{Out}/Hg_{In} × 100)

The data used in the sample calculation below are from a stack CMM value taken on 8/29/2009 at 9:57, and a Koppers inlet ST collected on 9/26/2009 at 9:36:

% Hg Removal = 100 – (1.01/9.43 × 100) = 89.29%

lb/hr to lb/Macf

Gas flow = Flue gas flow (calculated from combustion calculations) at the LC electrostatic precipitator inlet injection location adjusted to 350°F, in units of actual cubic feet per minute.

lb/hr = Material injection rate in lb/hr

lb/Macf (at 350°F) = (lb/hr)/(gas flow × 60) × 1000000

The data used in the sample calculation below are from the average value obtained using combustion calculations for a gross load of 737 MW. For the example calculation, a sorbent feed rate of 150 lb/hr is used:

lb/Macf (at 350°F) = (150 lb/hr)/(2,464,476 acfm [at 350°F] × 60) × 1000000 = 1.0 lb/Macf (at 350°F)

EPA METHOD 29 and 26A SAMPLING

Volume of Gas Sample

Vm(std) = Volume of gas sample measured by the dry gas meter, corrected to standard conditions, dscf

$$\text{Vm(std) (dscf)} = \frac{K_1 \times \text{Vmc} \times \text{Pm}}{\text{Tm} + 460}$$

$$\text{Vm(std)} = \frac{17.64 \times 55.835 \times 29.53}{76 + 460} = 54.272 \text{ dscf}$$

Where:

K_1 = 17.64 R/in. Hg
Vmc = Vm × Cm = Volume of gas sample as measured by dry gas meter, corrected for meter calibration (Cm = meter calibration coefficient) (dcf)
Pm = Meter pressure (in. Hg)
Tm = Meter temperature (°F)

Volume of Water Vapor

Vw(std) = Volume of water vapor in the gas sample, corrected to standard conditions, scf
Vw(std) (scf) = $K_2 \times H_2O(g)$
Vw(std) = 0.04715 × 261.1 = 12.311 scf

Where:
K_2 = 0.04715 ft^3/g
$H_2O(g)$ = Mass of liquid collected in impingers and silica gel (g)

Water Vapor in the Gas Stream

Bws = Water vapor in the gas stream, proportion by volume

$$\text{Bws} = \frac{\text{Vw(std)}}{\text{Vm(std)} + \text{Vw(std)}}$$

$$\text{Bws} = \frac{12.311}{54.272 + 12.311} = 0.1849$$

Dry Molecular Weight

Md = Dry molecular weight of stack gas, lb/lb-mol

Md (lb/lb-mol) = $0.440 \times (\%CO_2) + 0.320 \times (\%O_2) + 0.280 \times (\%N_2 + \%CO)$

Md = $0.440 \times 12.7 + 0.320 \times 6.7 + 0.280 \times 80.6 = 30.3$ lb/lb-mol

Where:

% (CO_2, O_2, N_2, CO) = Percent (CO_2, O_2, N_2, CO) by volume, dry basis

Molecular Weight

Ms = Molecular weight of stack gas, wet basis, lb/lb-mol

Ms (lb/lb-mol) = $Md \times (1 - Bws) + 18.0 \times Bws$

Ms = $30.3 \times (1 - 0.1849) + 18.0 \times 0.1849 = 28.0$ lb/lb-mol

Average Stack Gas Velocity

Vs = Average stack gas velocity, ft/sec

$$\text{Vs (ft/sec)} = K_3 \times Cp \times (\Delta p)^{1/2}(\text{avg}) \times \left[\frac{Ts + 460}{Ps \times Ms}\right]^{1/2}$$

$$\text{Vs} = 85.49 \times 0.84 \times 0.922 \times \left[\frac{132 + 460}{29.46 \times 28.0}\right]^{1/2} = 56.1\,\text{ft/sec}$$

Where:

$$K_3 = 85.49\,\text{ft/sec} \times \left[\frac{\frac{\text{lb}}{\text{lb-mole}} \times \text{in. Hg}}{\text{R} \times \text{in. } H_2O}\right]^{1/2}$$

Cp = Pitot tube coefficient, dimensionless

Δp = Velocity head of stack gas (in. Hg)

$(\Delta p)^{1/2}(\text{avg})$ = Average of the square root of Δp values

Ts = Stack gas temperature (°F)

Ps = Stack pressure (in. Hg)

Isokinetic Sampling Rate

I = Percent of isokinetic sampling, %

$$\text{I (\%)} = \frac{K_4 \times (Ts + 460) \times Vm(std) \times 144}{Ps \times Vs \times An \times \theta \times (1 - Bws)}$$

I = $$\frac{0.09450 \times (132+460) \times 54.272 \times 144}{29.46 \times 56.1 \times 0.0284 \times 120 \times (1-0.1849)} = 95\%$$

Where:

K_4 = $$\frac{0.09450\% \,(\text{in. Hg})(\text{min})}{\text{R} \times \text{sec}}$$

An = Cross-sectional area of nozzle (in.^{2})

θ = Total sampling time (min)

Volume of Gas Sample Corrected to 3% O_2

Vm*(std) = Volume of gas sample measured by the dry-gas meter (Vm[std])

Vm*(std) = $$K_5 \times \text{Vm}(\text{std}) \times \frac{21 - \%O_2}{18}$$

Vm*(std) = $$0.02832 \times 54.272 \times \frac{21 - 6.7}{18} = 1.221\,\text{Nm}^3$$

Where:

K_5 = 0.02832 m^3/ft^3

Method 29 – Mercury

Hg (µg/Nm^3) = $$\frac{\mu\text{g}}{\text{Vm}^*(\text{std})}$$

Hg = $$\frac{8.20}{1.221} = 6.71\ \mu\text{g/Nm}^3$$

Method 26A – Chloride

Cl ppmv = $$\frac{mg}{Vm(std)} \times 22.4 \div 35.453$$

Cl = $$\frac{\lhd 1.3}{0.591} \times 22.4 \div 35.453 \le 1.3\ \text{ppmv}$$

* corrected to 3% oxygen

APPENDIX E

U.S. ENVIRONMENTAL PROTECTION AGENCY M26A, M29, AND M5 DATA

U.S. ENVIRONMENTAL PROTECTION AGENCY M26A, M29, AND M5 DATA

Throughout the test project, U.S. Environmental Protection Agency (EPA) M26a, M29, and M5 testing was conducted during baseline and various injection tests at the Lodge Cottrell (LC) inlet and stack-sampling (STK) locations. The raw data from each test are presented in Tables E-1–E-5.

Table E-1. EPA M26a Data

Sample ID:	C81109LCIn-M26A	C81109STK-M26A	C90909LCIn-M26A	C90909STK-M26A
Date	08/11/09	08/11/09	09/09/09	09/09/09
Start Time	20:45	20:43	15:03	16:02
Run No.	1	1	1	1
Time, min	55.0	58.0	60.0	60.0
Ts, °F	352	134	345	132
Vm, dcf	21.341	27.558	25.029	28.037
Tm, °F	81	77	77	73
dH, in. H_2O	0.42	0.65	0.50	0.60
Pb, in. Hg	29.69	29.43	29.71	29.45
Pm, in. Hg	29.72	29.48	29.75	29.49
Static, in. H_2O	−19.00	−0.40	−18.00	−0.40
Ps, in. Hg	28.29	29.40	28.39	29.42
Dn, in.	0.158	0.190	0.158	0.190
An, in.^{2}	0.0196	0.0284	0.0196	0.0284
DP	1.50	0.85	1.22	0.85
SQRT(DP), °	1.225	0.922	1.105	0.922
Cm	1.009	0.999	1.009	0.999
H_2O, g	69.8	141.9	74.6	132.6
Dust, g	0.07715	0.00000	0.15082	0.00085
CO_2, %	14.2	13.4	13.7	12.8
O_2, %	5.0	5.9	5.5	6.6
N_2 + CO, %	80.8	80.7	80.8	80.6
Vmc, dcf	21.533	27.530	25.254	28.009
Vm(std), dscf	20.867	26.658	24.677	27.340
Vw(std), scf	3.291	6.691	3.517	6.252
Bws	0.1362	0.2006	0.1248	0.1861
Md, lb/lb-mole	30.5	30.4	30.4	30.3
Ms, lb/lb-mole	28.8	27.9	28.9	28.0
Vs, ft/sec	87.8	56.3	78.6	56.1
I, %	100	99	118	96
Vm*(std), Nm^3	0.525	0.633	0.602	0.619
Nm^3 at Stack O_2	0.591	0.755	0.699	0.774

* Corrected to 3% O_2.

Table E-2. EPA M26a Data

Sample ID:	C91009LCIn-M26A	C91009STK-M26A	C92609LCIn-M26A	C92609STK-M26A
Date	09/10/09	09/10/09	09/26/09	09/26/09
Start Time	10:15	10:13	12:38	12:18
Run No.	1	1	1	1
Time, min.	60.0	60.0	60.0	70.0
Ts, °F	337	132	343	132
Vm, dcf	23.131	25.888	23.907	34.663
Tm, °F	79	74	74	76
dH, in. H_2O	0.35	0.48	0.45	0.67
Pb, in. Hg	29.88	29.62	29.96	29.70
Pm, in. Hg	29.91	29.66	29.99	29.75
Static, in. H_2O	−19.00	−0.40	−19.00	−0.40
Ps, in. Hg	28.48	29.59	28.56	29.67
Dn, in.	0.159	0.190	0.159	0.190
An, in.^{2}	0.0199	0.0284	0.0199	0.0284
DP	1.20	0.61	1.60	0.85
SQRT(DP), °	1.095	0.781	1.265	0.922
Cm	1.009	0.999	1.009	0.999
H_2O, g	69.7	119.5	72.0	163.6
Dust, g	0.00000	0.00000	0.16240	0.00094
CO_2, %	14.1	12.8	13.0	12.6
O_2, %	5.1	6.5	6.3	6.8
N_2 + CO, %	80.8	80.7	80.7	80.6
Vmc, dcf	23.339	25.862	24.122	34.628
Vm(std), dscf	22.843	25.335	23.900	33.903
Vw(std), scf	3.286	5.634	3.395	7.714
Bws	0.1258	0.1819	0.1244	0.1854
Md, lb/lb-mole	30.5	30.3	30.3	30.3
Ms, lb/lb-mole	28.9	28.1	28.8	28.0
Vs, ft/sec	77.4	47.4	89.7	55.9
I, %	108	105	98	102
Vm*(std), Nm^3	0.571	0.578	0.553	0.757
Vm(std), Nm^3 at Stack O_2	0.647	0.717	0.677	0.960

* Corrected to 3% O_2.

Table E-3. EPA M29/M5 Data

Sample ID:	C90909LCIn-M29	C90909STK-M29	C91109LCIn-M29	C91109STK-M29
Date	09/09/09	09/09/09	09/11/09	09/11/09
Start Time	18:29	18:20	10:20	10:12
Run No.	1	1	1	1
Time, min	120.0	120.0	120.0	120.0
Ts, °F	346	132	347	132
Vm, dcf	48.041	55.891	48.018	58.118
Tm, °F	79	76	90	77
dH, in. H_2O	0.45	0.61	0.45	0.66
Pb, in. Hg	29.75	29.49	29.72	29.46
Pm, in. Hg	29.78	29.53	29.75	29.51
Static, in. H_2O	−18.00	−0.40	−19.00	−0.40
Ps, in. Hg	28.43	29.46	28.32	29.43
Dn, in.	0.159	0.190	0.159	0.190
An, in.^{2}	0.0199	0.0284	0.0199	0.0284
DP	1.60	0.85	1.60	0.85
SQRT(DP), °	1.265	0.922	1.265	0.922
Cm	1.009	0.999	1.009	0.999
H_2O, g	143.6	261.1	135.2	265.6
Dust, g	0.36173	0.00108	0.74955	0.00131
CO_2, %	13.6	12.7	13.7	12.6
O_2, %	5.6	6.7	5.5	6.8
N_2 + CO, %	80.8	80.6	80.8	80.6
Vmc, dcf	48.473	55.835	48.450	58.060
Vm(std), dscf	47.248	54.272	46.234	56.279
Vw(td), scf	6.771	12.311	6.375	12.523
Bws	0.1253	0.1849	0.1212	0.1820
Md, lb/lb-mole	30.4	30.3	30.4	30.3
Ms, lb/lb-mole	28.8	28.0	28.9	28.1
Vs, ft/sec	90.1	56.1	90.2	56.1
I, %	97	95	95	99
Vm*(std), Nm^3	1.145	1.221	1.127	1.257
Vm(std), Nm^3 at Stack O_2	1.338	1.537	1.309	1.594

* Corrected to 3% O_2.

Table E-4. EPA M29/M5 Data

Sample ID:	C91109LCIn-M29-2	C91109STK-M29-2	C91309LCIn-M29	C91309STK-M29
Date	09/11/09	09/11/09	09/13/09	09/13/09
Start Time	17:13	17:12	13:29	13:25
Run No.	1	1	1	1
Time, min	120.0	120.0	120.0	120.0
Ts, °F	357	133	347	132
Vm, dcf	50.011	59.784	49.470	59.421
Tm, °F	104	84	87	80
dH, in. H_2O	0.44	0.65	0.47	0.67
Pb, in. Hg	29.55	29.29	29.30	29.04
Pm, in. Hg	29.58	29.34	29.33	29.09
Static, in. H_2O	−19.00	−0.40	−19.50	−0.40
Ps, in. Hg	28.15	29.26	27.87	29.01
Dn, in.	0.159	0.190	0.159	0.190
An, in.^{2}	0.0199	0.0284	0.0199	0.0284
DP	1.60	0.85	1.60	0.85
SQRT(DP), °	1.265	0.922	1.265	0.922
Cm	1.009	0.999	1.009	0.999
H_2O, g	139.0	279.1	140.6	269.7
Dust, g	0.53371	0.00000	0.59321	0.00029
CO_2, %	13.9	13.0	13.6	12.0
O_2, %	5.3	6.3	5.7	6.6
N_2 + CO, %	80.8	80.7	80.7	81.4
Vmc, dcf	50.461	59.724	49.915	59.362
Vm(std), dscf	46.688	56.817	47.220	56.408
Vw(std), scf	6.554	13.160	6.629	12.716
Bws	0.1231	0.1881	0.1231	0.1840
Md, lb/lb-mole	30.4	30.3	30.4	30.2
Ms, lb/lb-mole	28.9	28.0	28.9	27.9
Vs, ft/sec	91.0	56.3	91.0	56.6
I, %	97	101	98	100
Vm*(std), Nm^3	1.153	1.314	1.137	1.278
Vm(std), Nm^3 at Stack O_2	1.322	1.609	1.337	1.597

* Corrected to 3% O_2.

Table E-5. EPA M29/M5 Data

Sample ID:	C91409LCIn-M29	C91409STK-M29	C91509LCIn-M29	C91509STK-M29
Date	09/14/09	09/14/09	09/15/09	09/15/09
Start Time	10:29	10:30	12:44	12:36
Run No.	1	1	1	1
Time, min	120.0	120.0	120.0	120.0
Ts, °F	345	131	352	132
Vm, dcf	49.418	59.031	48.853	59.508
Tm, °F	75	76	97	79
dH, in. H_2O	0.47	0.67	0.43	0.65
Pb, in. Hg	29.60	29.34	29.72	29.46
Pm, in. Hg	29.63	29.39	29.75	29.51
Static, in. H_2O	−19.50	−0.40	−19.50	−0.40
Ps, in. Hg	28.17	29.31	28.29	29.43
Dn, in.	0.159	0.190	0.159	0.190
An, in.^{2}	0.0199	0.0284	0.0199	0.0284
DP	1.50	0.85	1.50	0.85
SQRT(DP), °	1.225	0.922	1.225	0.922
Cm	1.009	0.999	1.009	0.999
H_2O, g	141.4	262.7	134.6	272.2
Dust, g	0.66746	0.00122	0.26357	0.00061
CO_2, %	13.7	12.6	13.8	12.9
O_2, %	5.5	6.8	5.4	6.4
N_2 + CO, %	80.8	80.6	80.8	80.7
Vmc, dcf	49.863	58.972	49.293	59.448
Vm(std), dscf	48.721	57.039	46.445	57.410
Vw(std), scf	6.667	12.386	6.346	12.834
Bws	0.1204	0.1784	0.1202	0.1827
Md, lb/lb-mole	30.4	30.3	30.4	30.3
Ms, lb/lb-mole	28.9	28.1	28.9	28.1
Vs, ft/sec	87.4	56.1	87.6	56.0
I, %	103	100	99	101
Vm*(std), Nm^3	1.188	1.274	1.140	1.319
Vm(std), Nm^3 at Stack O_2	1.380	1.615	1.315	1.626

* Corrected to 3% O_2.

APPENDIX F

PLANT DATA

PLANT DATA

Continuous (every 6 seconds) data were provided by the plant in a daily format. These data were compiled and are shown in the following graphs. A fair number of significant load drops, primarily done to clear slag buildup in the furnace, affected testing. The data from these time periods were not representative and were, therefore, removed from the mercury capture dataset. The September data for SO_2 and reagent feed show several minor upsets to the scrubber during the month. The only time this affected testing was on September 14 when the upset was of significant duration to cause the loss of Hg capture in the scrubber. The opacity monitors appear to have problems starting in late August. This may be an issue resulting from injection of activated carbon sorbents, but it is presumed to be a measurement problem not an opacity problem. All other data shows consistent operation for the test duration.

Table F-1. Plant Data Monthly Averages

Parameter	August Average	September Average	October Average	Overall Average
Air Preheater Differential Pressure, in. H_2O				
No. 22 Gas Side	10.45	10.62	10.38	10.48
No. 21 Gas Side	7.88	7.75	7.87	7.83
No. 22 Air Side	4.98	5.17	5.04	5.06
No. 21 Air Side	5.08	5.17	4.96	5.07
Fuel Flow, Klb/hr	867	822	847	845
Gross Load, MW	685	676	682	681
Mills in Service	7	7	7	7
O_2, %				
Stack O_2	5.87	6.44	6.10	6.14
No. 22 Boiler Exit	3.10	4.07	3.48	3.55
No. 21 Boiler Exit	2.72	2.71	2.70	2.71
Opacity, %				
No. 22	7.2	9.9	9.6	8.9
No. 21	8.2	4.4	4.0	5.5
Reagent Feed, gpm	53.4	45.0	34.3	44.2
Pumps in Service	2	2	2	2
Absorber Density	1.143	1.154	1.150	1.149
Stack NO_x, ppm	147	140	147	145
Stack SO_2, ppm	33	15	19	22
Temperature, °F				
No. 22 APH Inlet	846	832	828	835
No. 21 APH Inlet	842	828	826	832
Scrubber Inlet	347	335	327	336

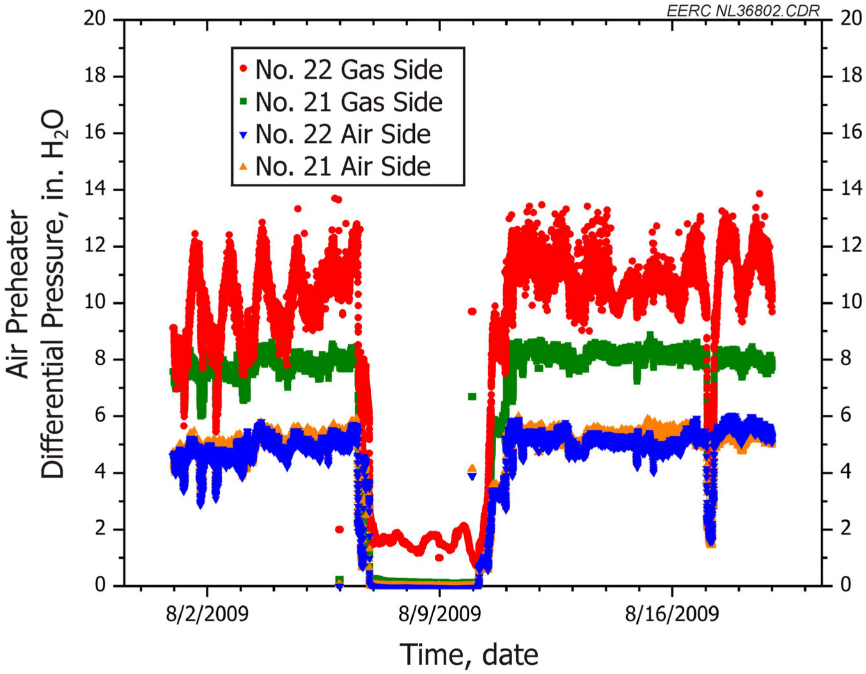


Figure F-1. August air preheater differential pressure.

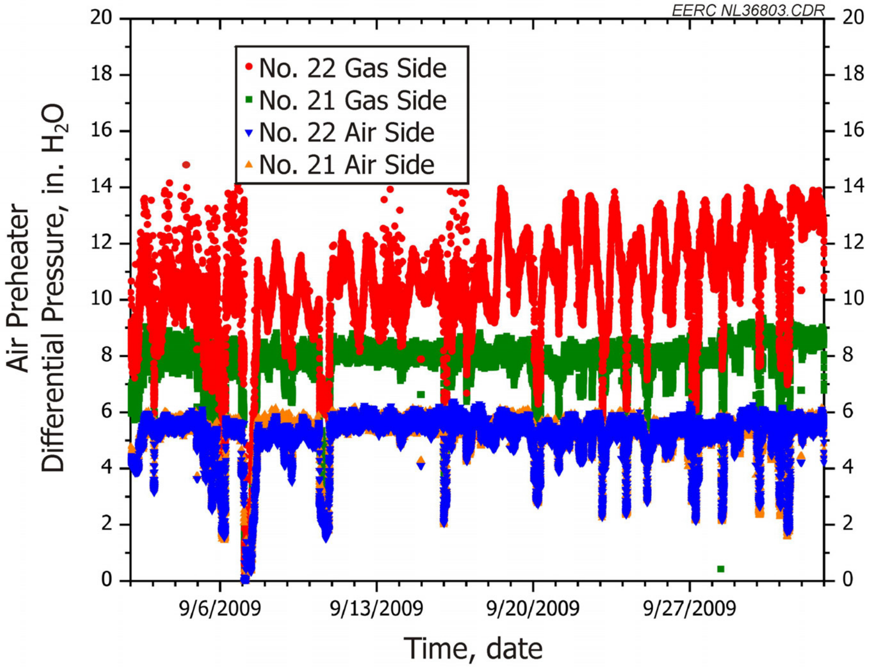


Figure F-2. September air preheater differential pressure.

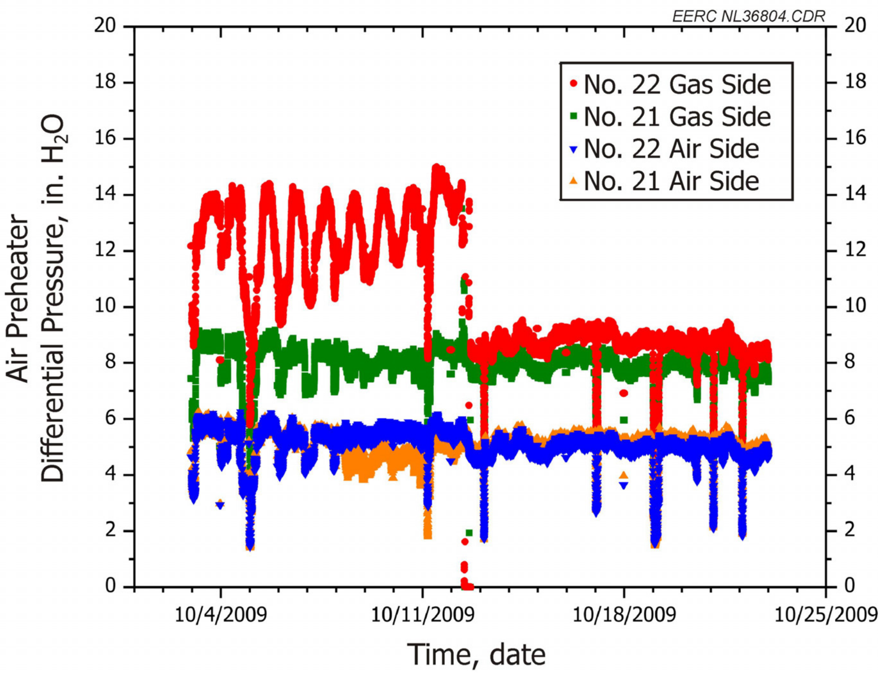


Figure F-3. October air preheater differential pressure.

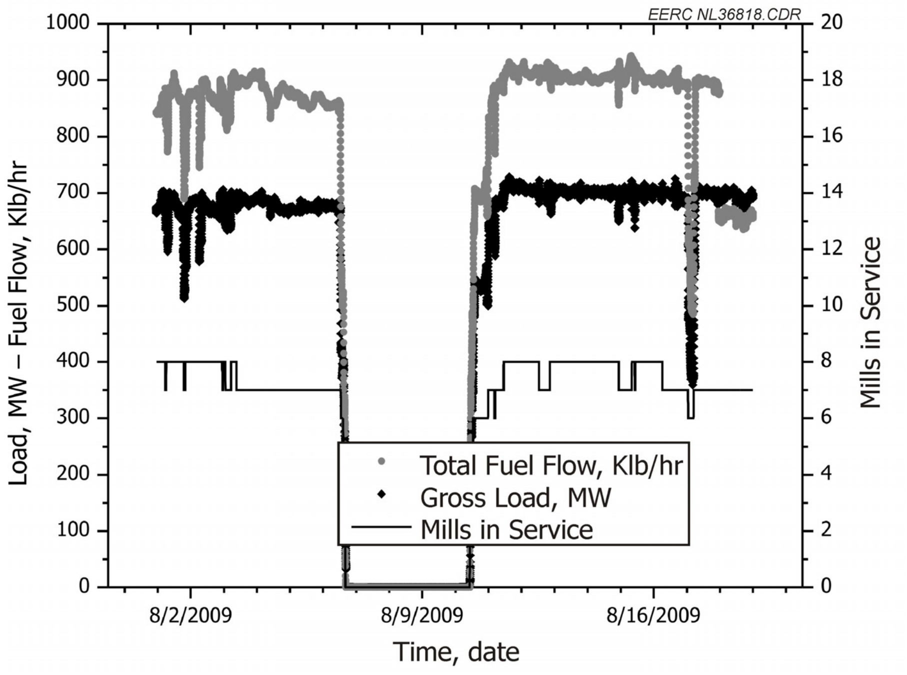


Figure F-4. August gross load, total fuel flow, and mills in service.

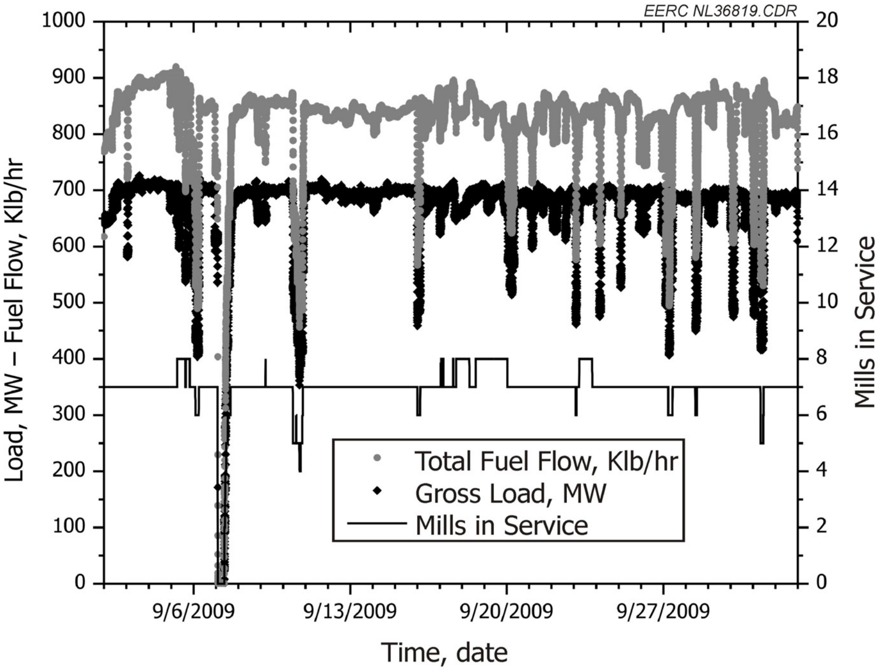


Figure F-5. September gross load, total fuel flow, and mills in service.

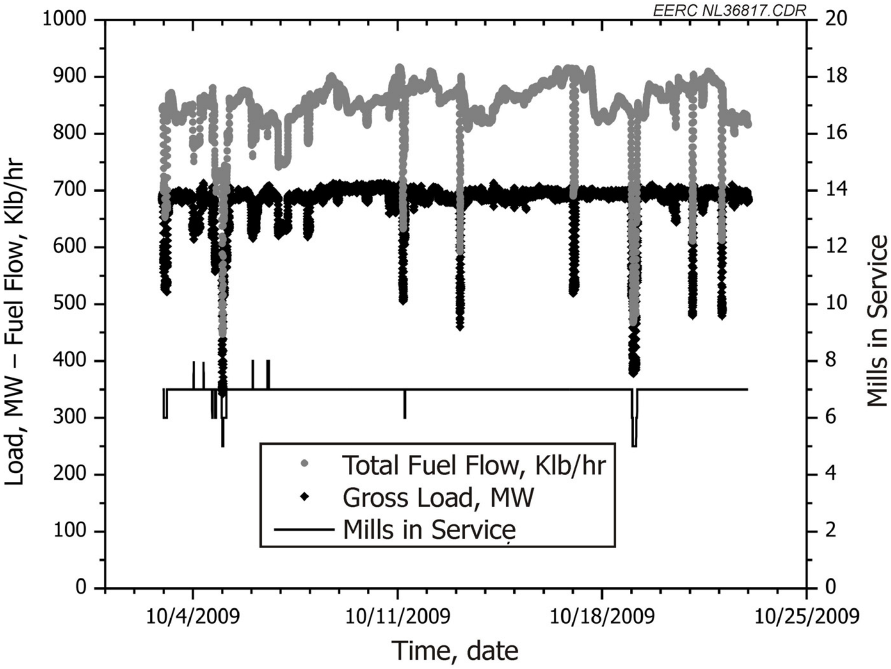


Figure F-6. October gross load, total fuel flow, and mills in service.

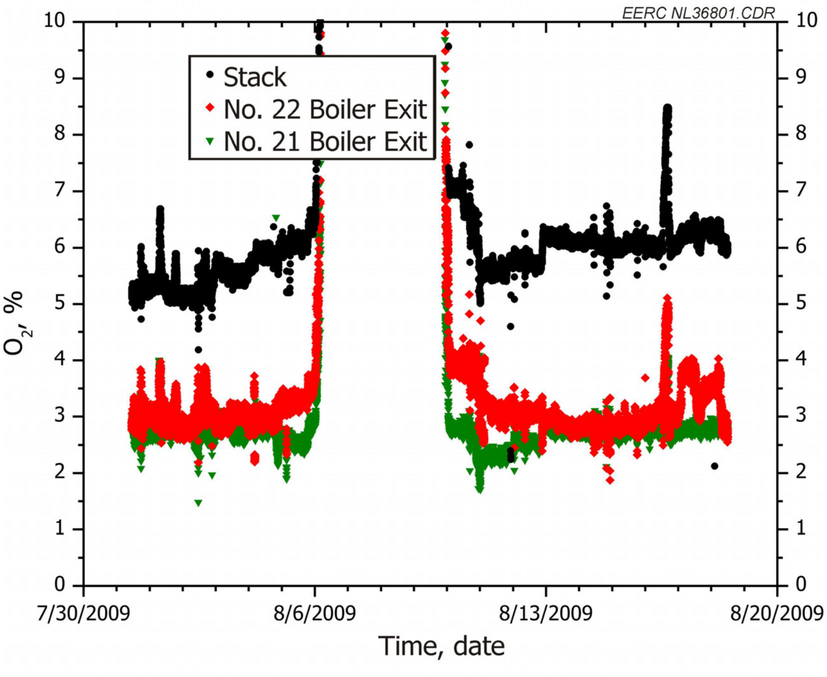


Figure F-7. August boiler exit and stack O_2.

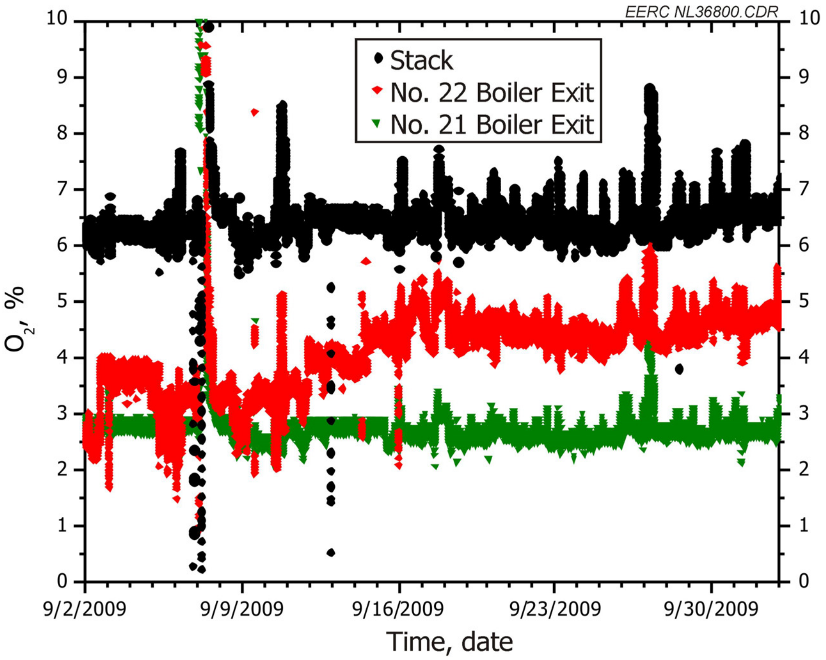


Figure F-8. September boiler exit and stack O_2.

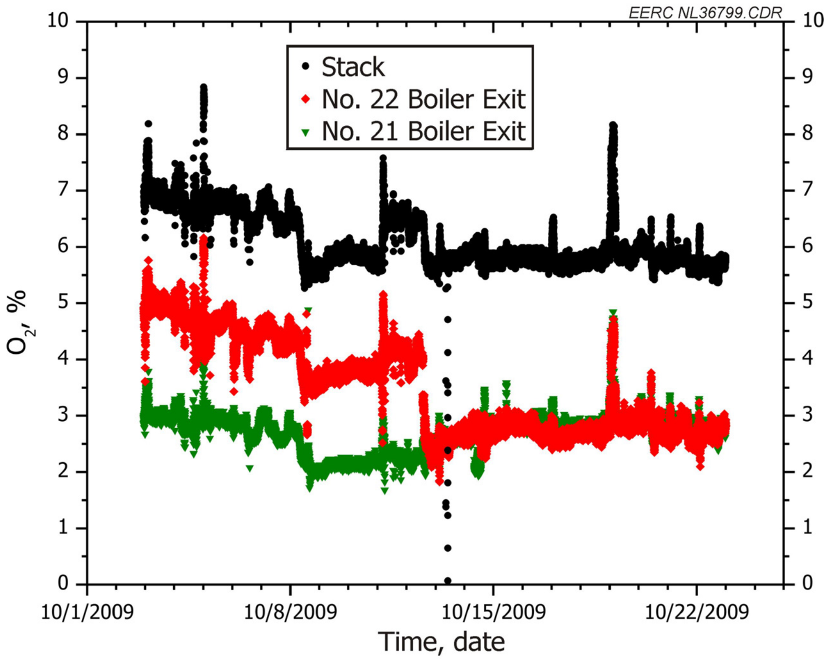


Figure F-9. October boiler exit and stack O_2.

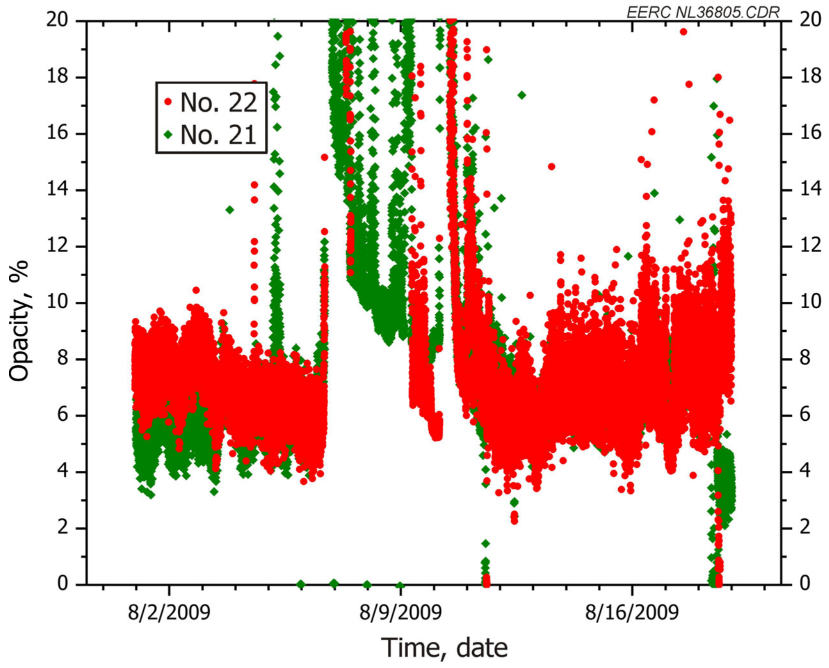


Figure F-10. August opacity data.

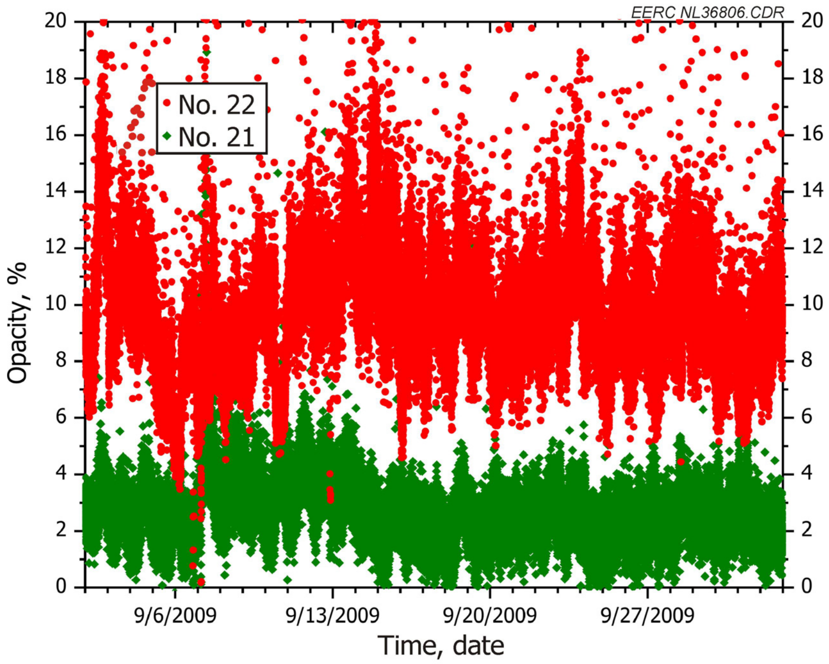


Figure F-11. September opacity data.

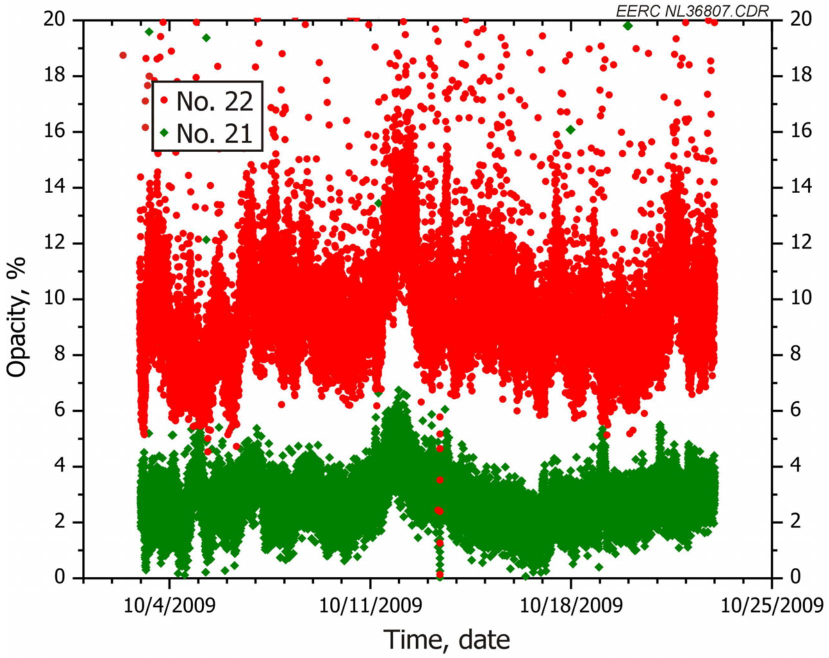


Figure F-12. October opacity data.

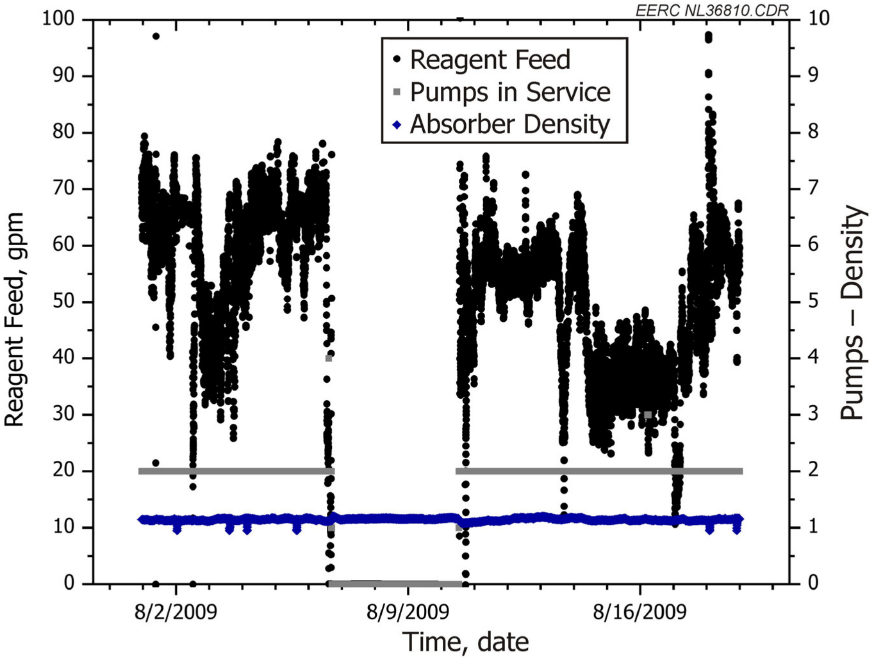


Figure F-13. August scrubber reagent feed rate, absorber density, and pumps in service.

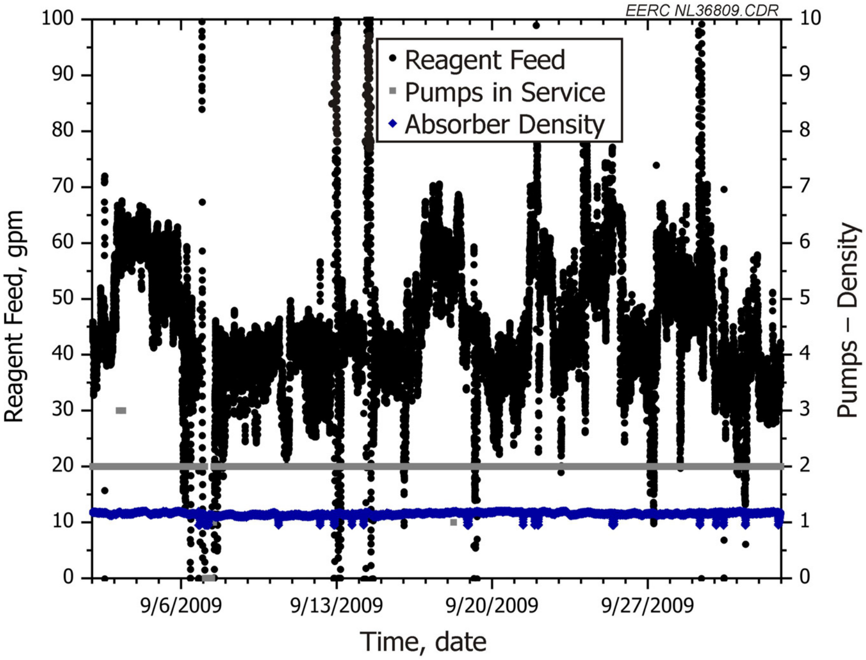


Figure F-14. September scrubber reagent feed rate, absorber density, and pumps in service.

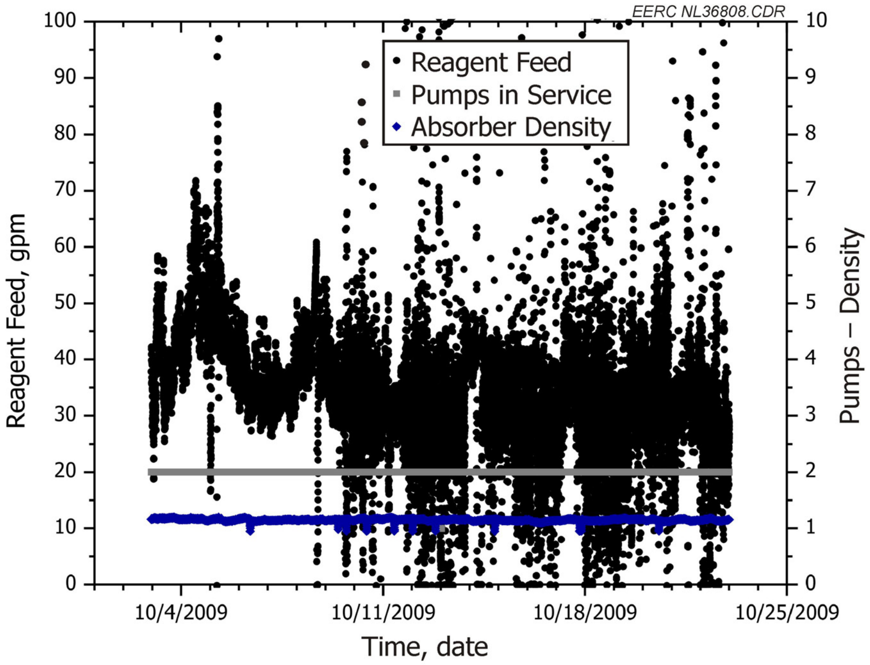


Figure F-15. October scrubber reagent feed rate, absorber density, and pumps in service.

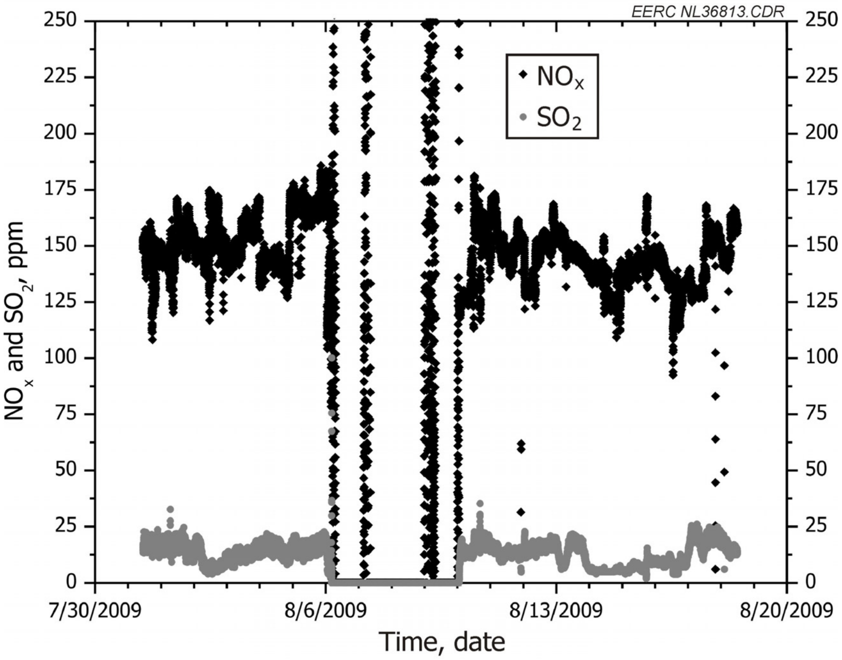


Figure F-16. August NO_x and SO_2 stack emission data.

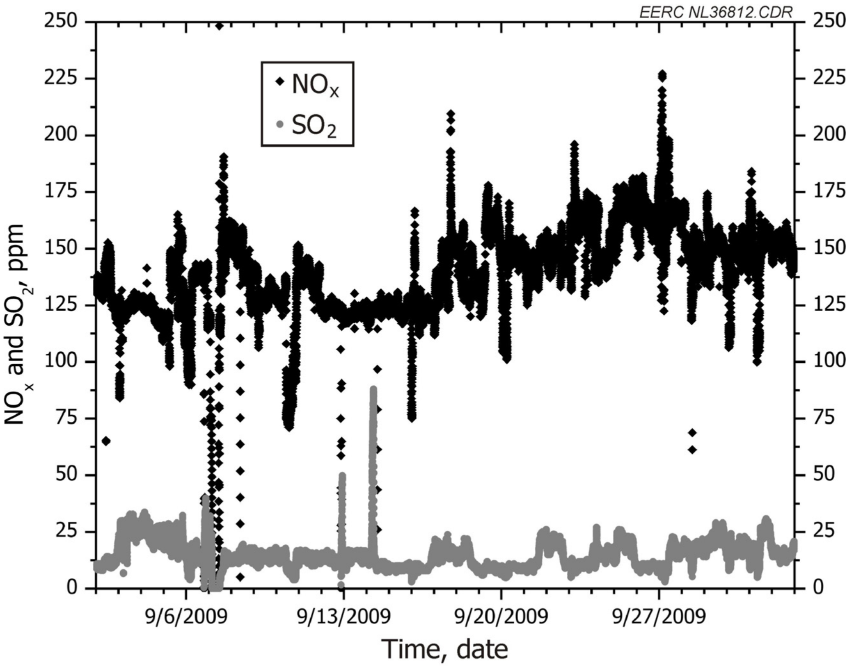


Figure F-17. September NO$_x$ and SO$_2$ stack emission data.

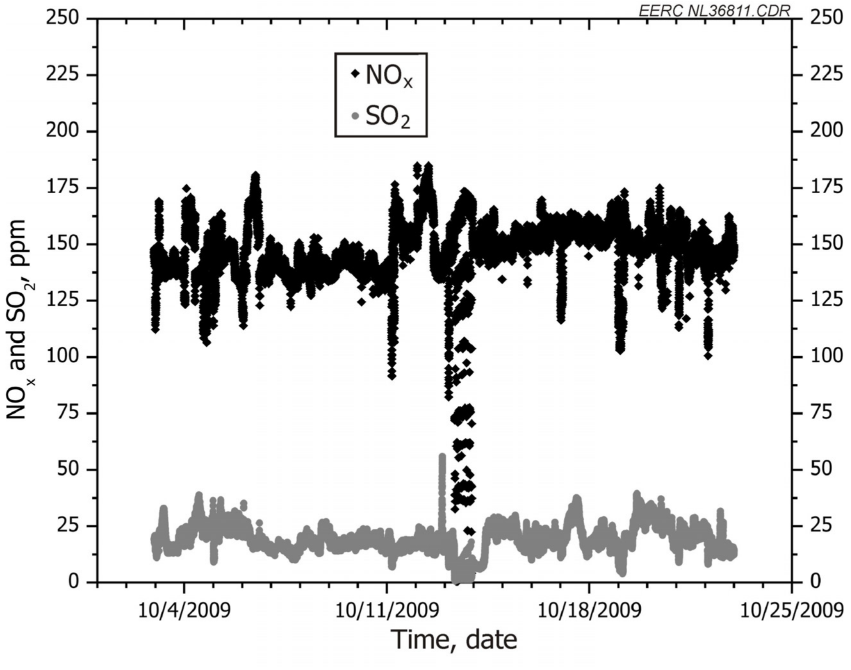


Figure F-18. October NO$_x$ and SO$_2$ stack emission data.

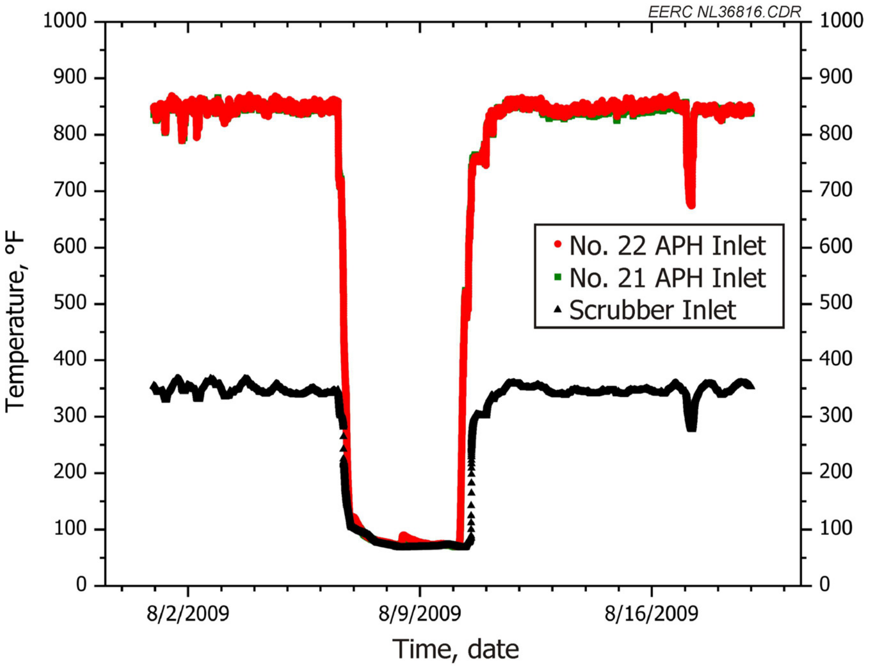


Figure F-19. August air preheater inlet and scrubber inlet flue gas temperatures.

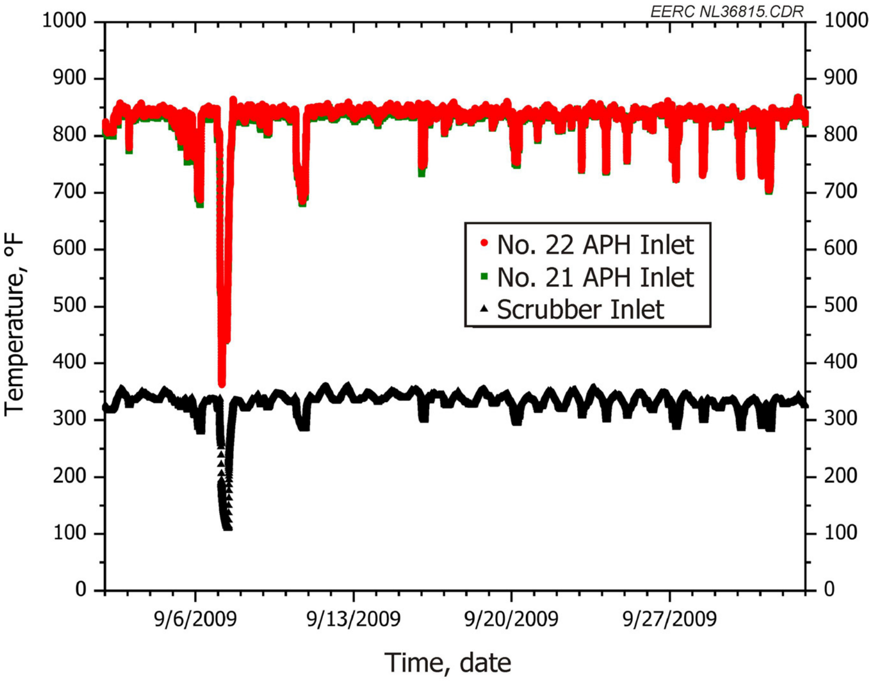


Figure F-20. September air preheater inlet and scrubber inlet flue gas temperatures.

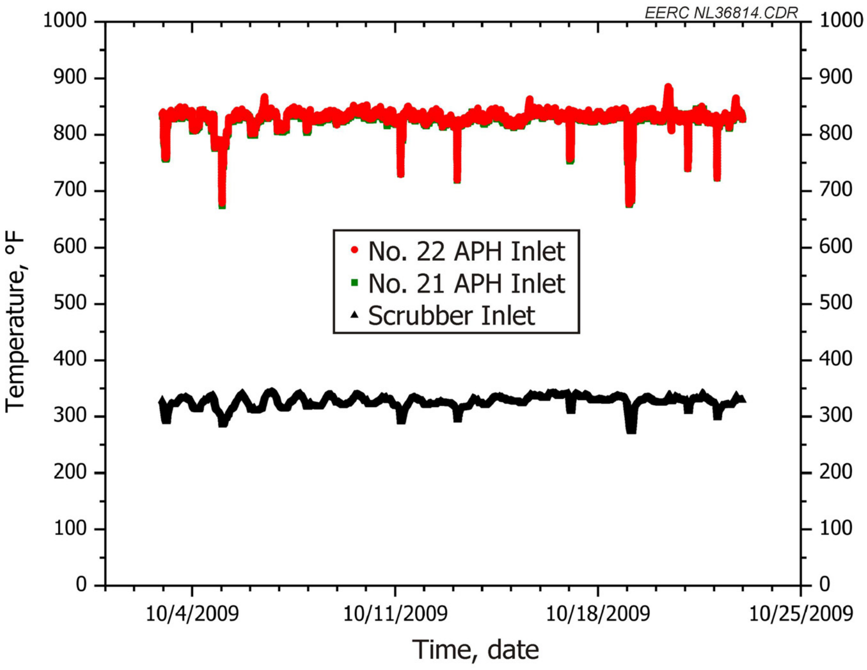


Figure F-21. October air preheater inlet and scrubber inlet flue gas temperatures.

APPENDIX G

ELECTROSTATIC PRECIPITATOR DATA

ELECTROSTATIC PRECIPITATOR (ESP) DATA

ESP data including amperage, voltage, and spark rate were monitored throughout the duration of the test program. The monthly ESP data for each field in the Lodge ESPs are presented in Figures G-1 to G-6.

.

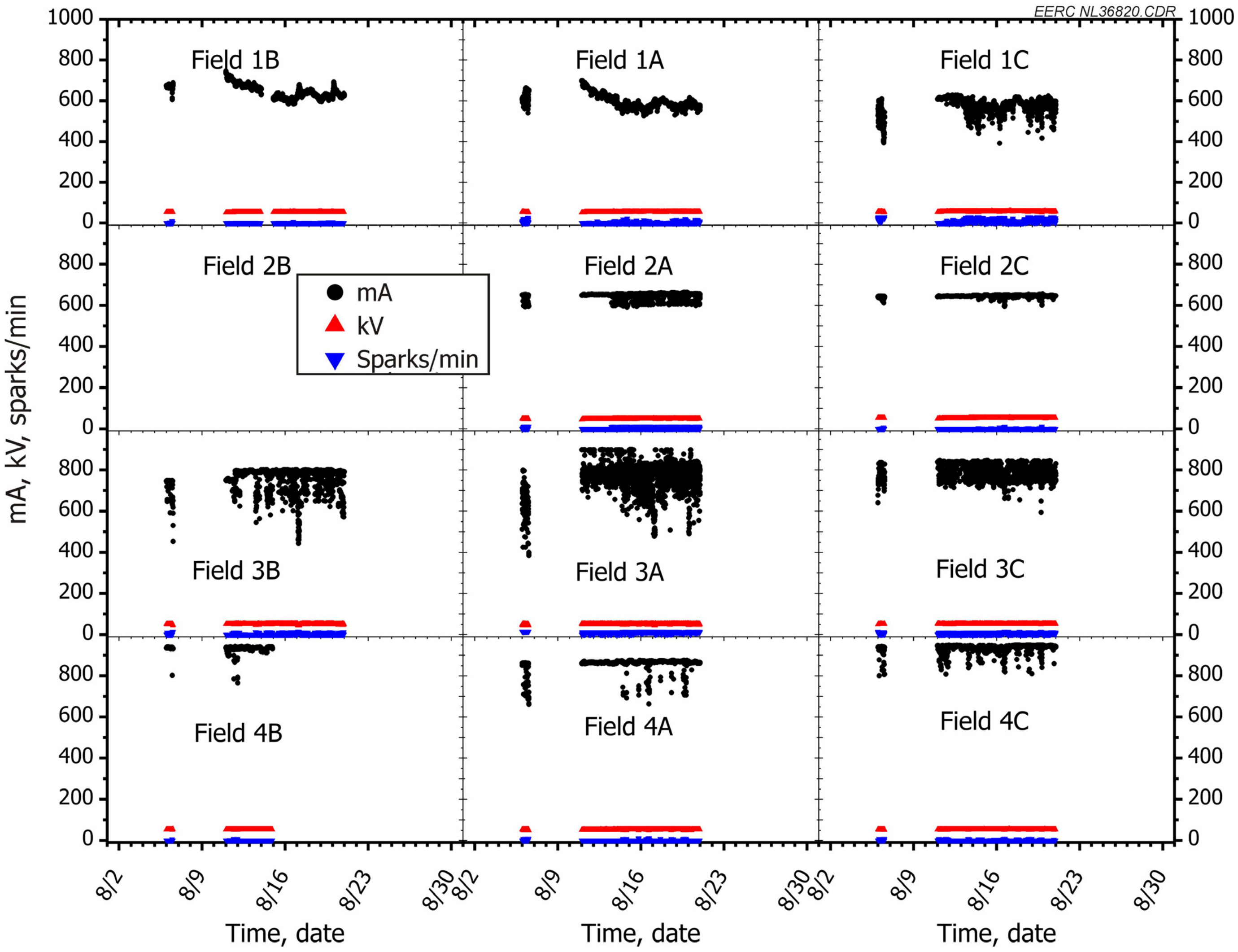


Figure G-1. August LC 21 ESP data.

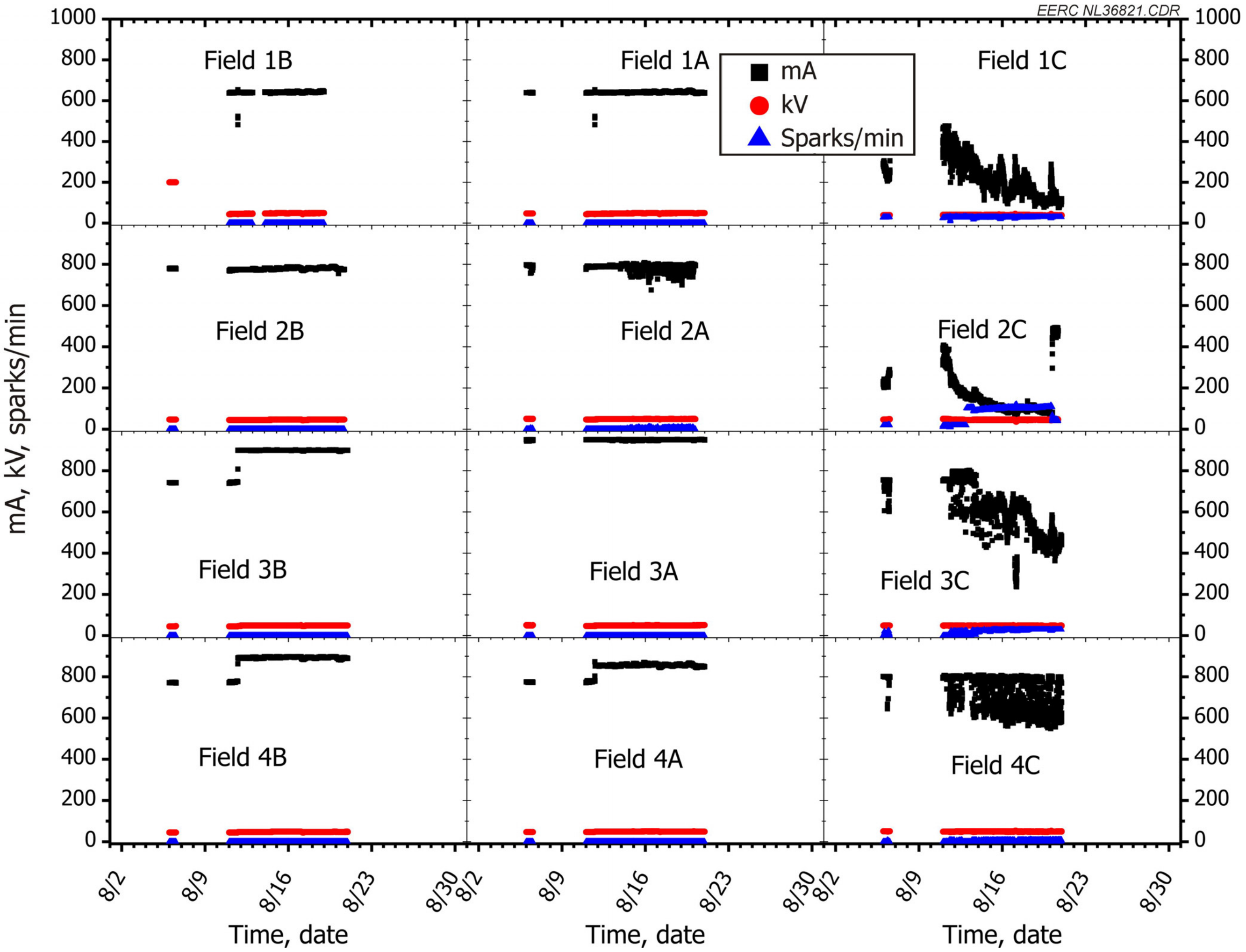


Figure G-2. August LC 22 ESP data.

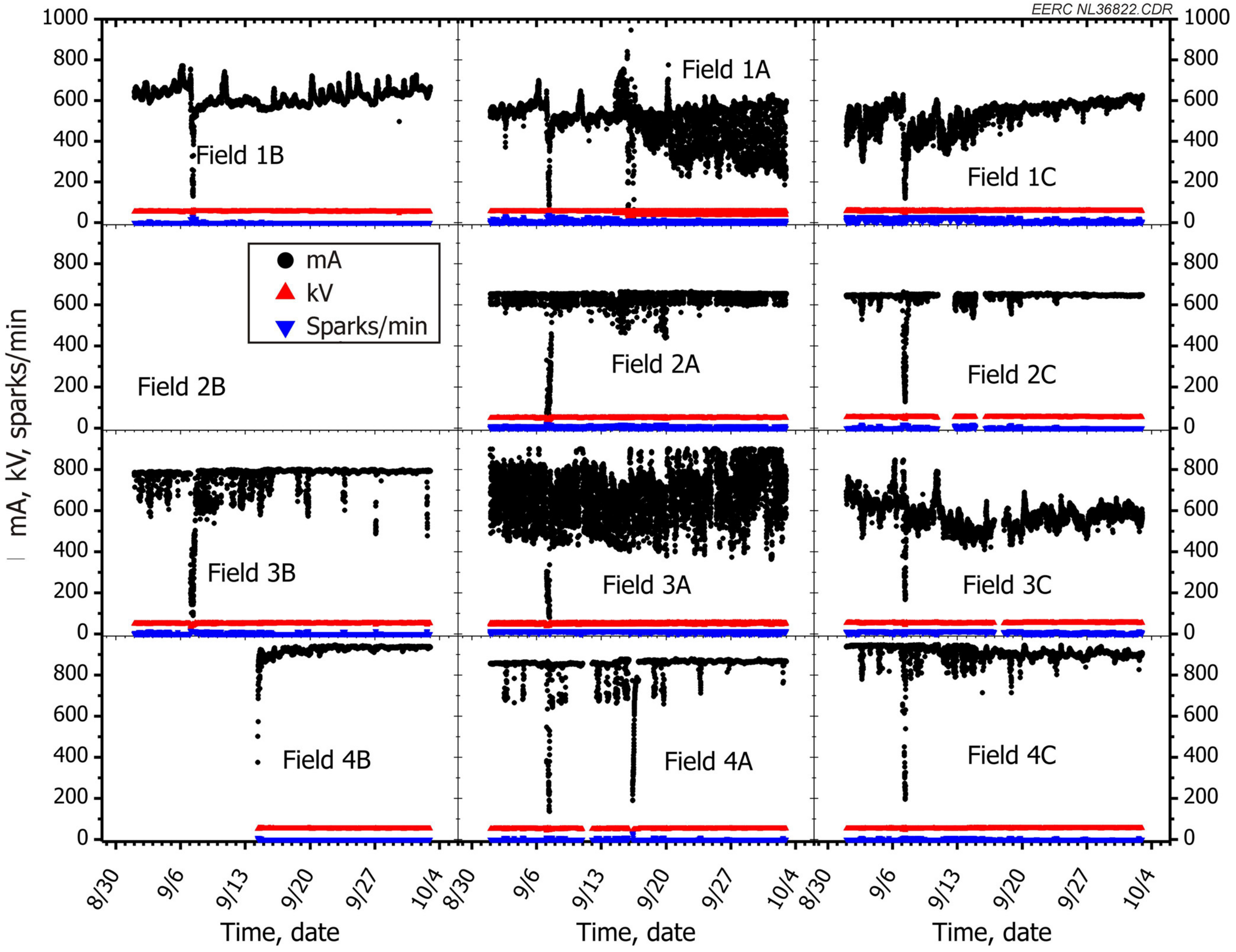


Figure G-3. September LC 21 ESP data.

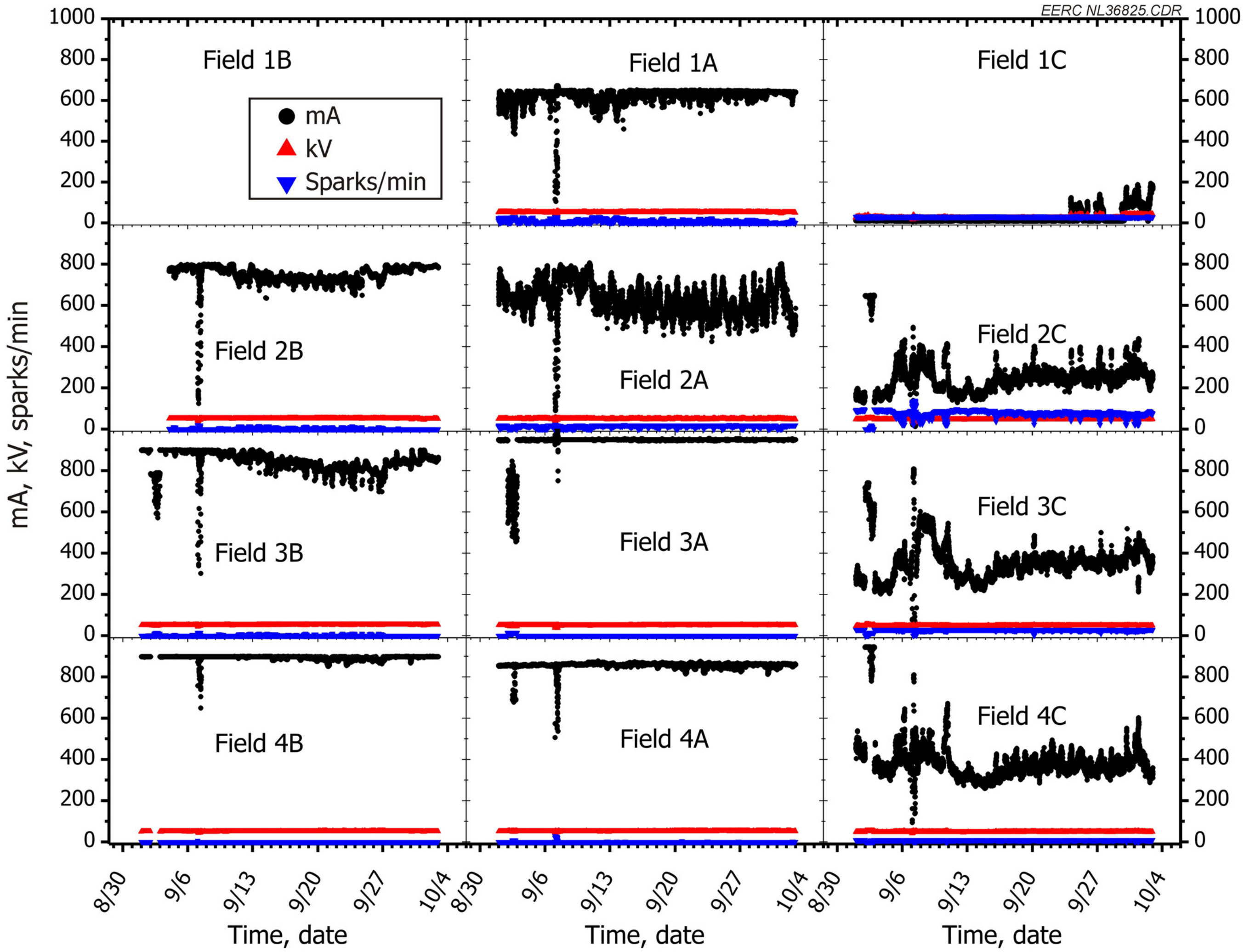


Figure G-4. September LC 22 ESP data.

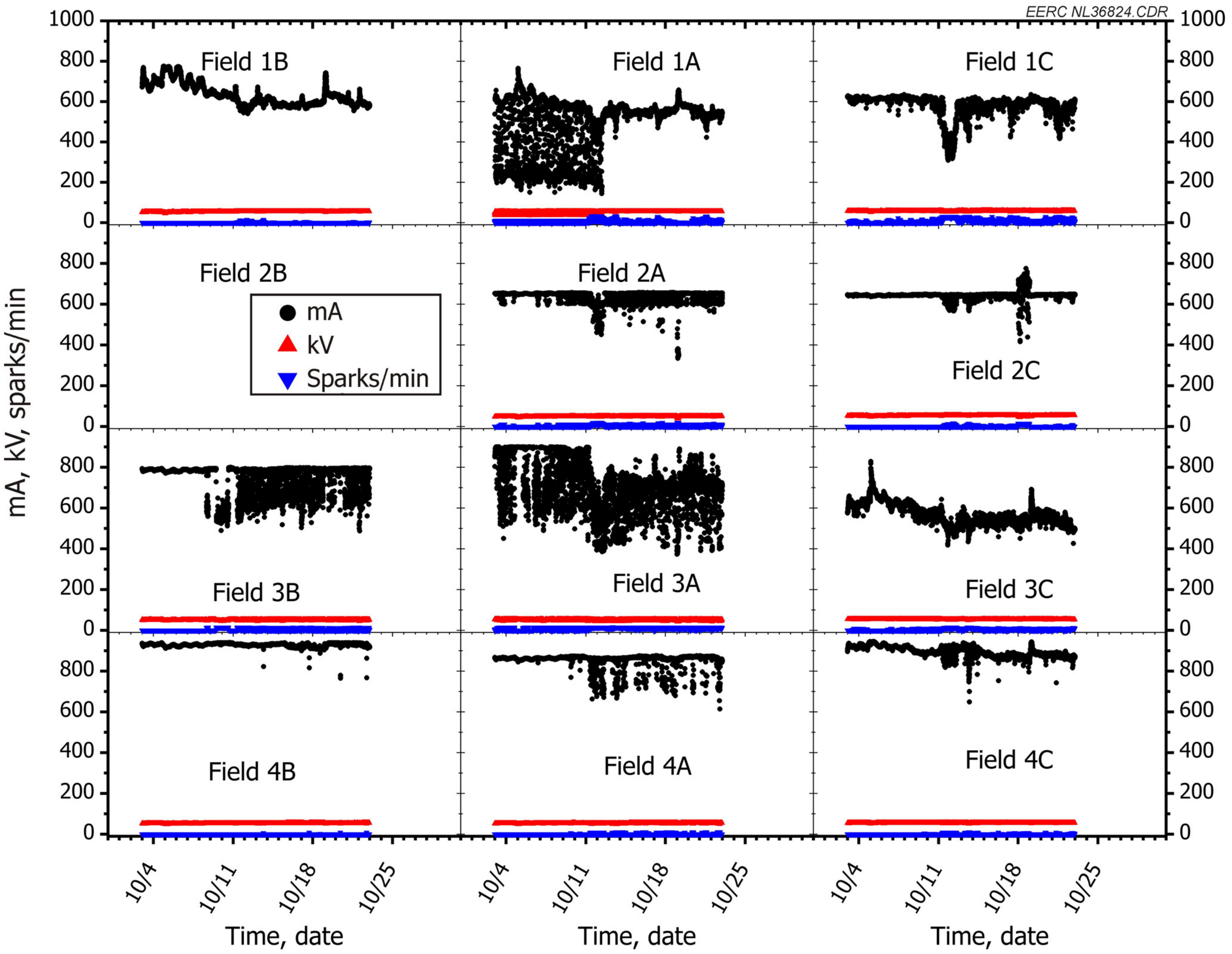


Figure G-5. October LC 21 ESP data.

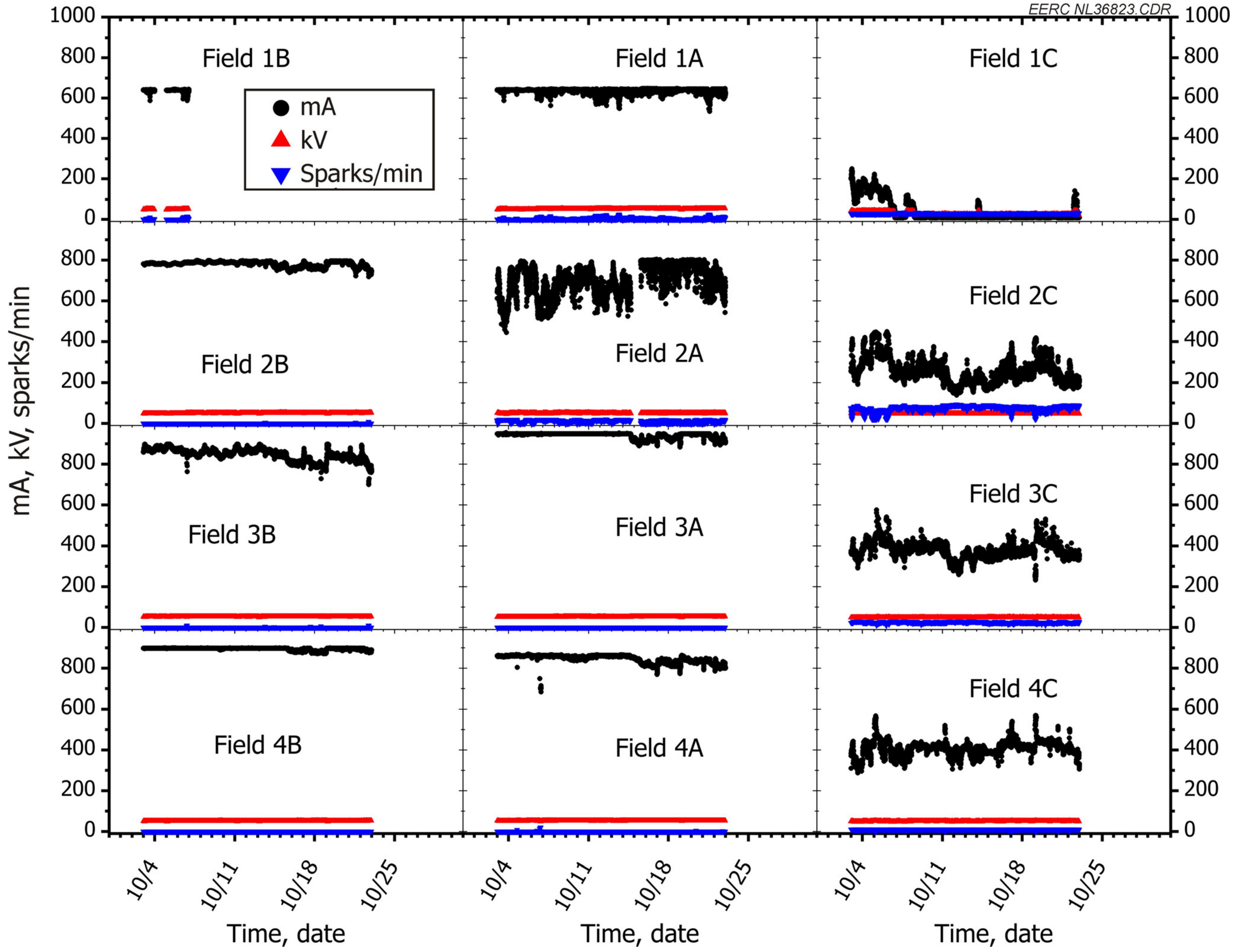


Figure G-6. October LC 22 ESP data.

APPENDIX H

ESP ASH DATA

ESP ASH DATA

Ash samples were collected from both the north and south sided of the test unit and analyzed for Hg, Cl and Br, and loss on ignition (LOI) during baseline and extended test conditions. The ash data for both the Koppers (K) and Lodge (LC) ESPs are presented in Tables H-1 and H-2.

Table H-1. ESP Ash Data

Test Condition	Date	9/8/09	9/9/09	9/11/09	9/13/09	9/14/09	9/15/09	9/17/09	9/18/09
Hg	µg/g (dry)								
Sample ID	K21	0.0295	0.0317		0.111	0.418	0.296	9.06	0.138
	K22	0.0318	0.0355	0.0683	0.0577	0.108	0.127	0.135	0.0463
	LC21	0.0274	0.0253	0.0214	0.135	1.6	6.64	7.88	
	LC22	0.0607	0.0456	0.0328	0.0376	0.012	0.191	0.12	0.0586
Cl and Br	µg/g (dry)								
Sample ID	K21	20.5	16.8		24.4	21.8	41	178	45.2
	K22	16.9	15.6	13.4	19.1	20.7	40.3	66.5	41.4
	LC21	34.2	33.9	36.4	37.6	60.6	145	169	
	LC22	41.8	34.1	37.1	45.9	93	57.1	65	63.1
LOI	%								
Sample ID	K21	0.14	0.11		0.16	0.16	0.23	2.65	0.17
	K22	0.21	0.2	0.18	0.18	0.22	0.2	0.41	0.14
	LC21	0.44	0.34	0.49	0.49	0.85	2.01	2.99	
	LC22	0.76	0.45	0.63	0.53	1.48	0.5	0.6	0.86

Table H-2. ESP Ash Data

Test Condition	Date	9/21/09	9/23/09	9/24/09	9/25/09	9/26/09	9/27/09	9/28/09	10/5/09
Hg	µg/g (dry)								
Sample ID	K21	0.147	0.193	0.234	0.228	0.226	0.281	0.344	0.128
	K22	0.0924	0.0681	0.0797	0.113	0.0593	0.0972	0.0964	0.0295
	LC21	10.7	11.8	11.9	12.6	12.2	5.45	5.93	1.87
	LC22	0.0225	0.116	2.18	8.3	5.75	4.73	6.18	1.96
Cl and Br	µg/g (dry)								
Sample ID	K21	81.3	30.3	34.1	41.5	111	94.2	57	22.1
	K22	52.4	31.5	24.9	39.2	49.9	81.3	58.1	15.6
	LC21	251	331	258	255	275	331	294	89.7
	LC22	77.7	53.2	98.5	245	240	391	357	149
LOI	%								
Sample ID	K21	0.23	0.16	0.16	0.21	0.22	0.23	0.18	0.21
	K22	0.16	0.13	0.14	0.19	0.21	0.27	0.24	0.14
	LC21	4.21	6.33	5.16	4.51	4.26	4.25	3.94	1.84
	LC22	1.32	0.55	1.28	4.09	3.84	5.34	6.02	2.4

APPENDIX I

SCRUBBER DATA

SCRUBBER DATA

Scrubber samples were collected during baseline and extended test periods in order to examine potential impacts to the scrubber from the test project. The reagent feed (solid and liquid), recycle slurry (solid and liquid), and gypsum were all analyzed for mercury. Tables I-1–I-4 display the scrubber mercury analysis data.

Table I-1. Scrubber Hg Data

Test Condition						
Date	9/8/09	9/9/09	9/10/09	9/13/09	9/14/09	9/15/09
Time	16:00	20:00	20:00	16:30	10:00	8:00
Hg						
Reagent Feed						
Liquid, µg/L (wet)	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Solid, µg/g (dry)	0.023	0.0261	0.0236	0.0229	0.0233	0.024
% Solids, %	24.4	24.9	19.5	24.4	24	24.8
Recycle Slurry						
Liquid, µg/L (wet)	0.23	0.30	0.40	0.60	65.20	0.80
Solid, µg/g (dry)	3.76	3.34	3.39	2.16	3.83	3.10
% Solids, %	11.80	14.30	12.50	19.60	11.80	13.00
Gypsum						
Solid, µg/g (dry)	2.32	0.845	0.978	0.857	0.711	0.81

Table I-2. Scrubber Hg Data

Test Condition						
Date	9/16/09	9/17/09	9/18/09	9/19/09	9/20/09	9/21/09
Time	8:15	8:00	8:40	13:00	8:15	8:40
Hg						
Reagent Feed						
Liquid, µg/L (wet)	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Solid, µg/g (dry)	0.0238	0.0218	0.0215	0.0232	0.0237	0.0208
% Solids, %	24.2	23.8	22.9	24.30	24.1	24.6
Recycle Slurry						
Liquid, µg/L (wet)	0.50	0.50	0.60	0.53	0.60	0.40
Solid, µg/g (dry)	2.09	3.85	2.43	2.60	3.83	3.31
% Solids, %	15.60	14.90	16.60	18.3	17.70	14.30
Gypsum						
Solid, µg/g (dry)	0.698	0.762	1.05	1.01	0.889	1.06

Table I-3. Scrubber Hg Data

Test Condition						
Date	9/22/09	9/23/09	9/24/09	9/25/09	9/26/09	9/27/09
Time	8:00	9:00	8:00	11:20	14:30	8:45
Hg						
Reagent Feed						
Liquid, µg/L (wet)	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Solid, µg/g (dry)	0.0203	0.0208	0.0204	0.0214	0.0203	0.0217
% Solids, %	25.6	23.6	22.8	23.20	23.50	24.03
Recycle Slurry						
Liquid, µg/L (wet)	0.20	0.20	0.10	0.10	0.10	0.90
Solid, µg/g (dry)	4.14	3.61	3.44	4.64	2.44	3.39
% Solids, %	18.70	16.70	16.10	15.1	16.2	13.48
Gypsum						
Solid, µg/g (dry)	0.966	1.17	1.17	1.12	0.994	4.9

Table I-4. Scrubber Hg Data

Test Condition					
Date	9/28/09	9/29/09	9/30/09	10/5/09	10/6/09
Time	13:30	8:30	9:45	8:00	4:30
Hg					
Reagent Feed					
Liquid, µg/L (wet)	<0.1	<0.1	<0.1	<0.1	<0.1
Solid, µg/g (dry)	0.0235	0.0219	0.0242	0.0241	0.0231
% Solids, %	24.25	23.66	29.74	29.17	31.08
Recycle Slurry					
Liquid, µg/L (wet)	0.80	0.80	0.40	0.20	0.30
Solid, µg/g (dry)	3.76	3.21	3.04	5.00	4.65
% Solids, %	12.31	12.39	15.10	11.81	13.96
Gypsum					
Solid, µg/g (dry)	5.64	5.07	3.81	5.87	5.54

APPENDIX J

MASS BALANCE DATA

MASS BALANCE DATA

The complete mass balance data set for the Hg mass balance calculations is presented in Table J-1. Tables J-2 and J-3 present the hazardous air pollutant (HAP) mass balance calculations for the baseline and SF10–SB24 ET1 test periods.

Table J-1. Hg Mass Balance Data

	Baseline	ET1	ET2	ET3
SF10, lb/hr	0	20	25	38
SB24, lb/hr	0	50	100	150
Net MW	700	700	700	700
Coal Feed Rate, tons/hr	440	422	435	440
% Ash	3.66	3.47	4.69	3.93
Fly Ash Split	75	75	75	75
Bottom Ash Split	25	25	25	25
Coal, lb/hr	846,000	844,000	870,000	880,000
Hg Conc., ppm	0.054	0.048	0.053	0.057
Hg, µlb/hr	45,684	40,512	46,110	50,160
Total Ash, lb/hr	30,963.6	29,286.8	40,803	34,584
Fly Ash, lb/hr	23,223	21,965	30,602	25,938
SEA, lb/hr	0	20	25	38
Koppers				
Efficiency, %	85.7	85.7	85.7	85.7
Ash Collected, lb/hr	19,902	18,841	26,248	22,261
Hg Conc., ppm	0.039	0.186	0.112	0.150
Hg, µlb/hr	784	3504	2940	3339
Sorbent, lb/hr	0	50	100	150
Ash Pre-LC, lb/hr	3321	3194	4480	3865
LC				
Efficiency, %	95.1	95.1	95.1	95.1
Ash Collected, lb/hr	3158	3037	4260	3675
Hg Conc., ppm	0.0355	3.42	6.06	9.71
Hg, µlb/hr	112	10,388	25,817	35,686
Overall Eff., %	99.3	99.3	99.3	99.3

Continued…

Table J-1. Hg Mass Balance Data (continued)

	Baseline	ET1	ET2	ET3
Scrubber				
Reagent Feed, lb/hr	25,507	23,813	26,147	26,561
% Solids, %	23.9	24.4	23.9	23.3
Solids In, lb/hr	6088	5810	6249	6189
Solids Out, lb/hr	7573	7228	7774	7699
Hg Reagent Feed Solid, ppm	0.024	0.024	0.022	0.020
Hg Conc., ppm	1.38	0.77	0.96	1.11
Hg, µlb/hr	10,305	5429	7295	8418
Stack				
Flow, dNm^3 at 3% O$_2$/min	39,536	39,562	39,599	39,446
Hg Conc., µg/dNm^3 at 3% O$_2$	8.44	3.37	1.54	1.09
Hg, µlb/hr	44,099	17,620	8059	5682
Induced Draft (ID) Fan Out				
Flow, dNm^3 at 3% O$_2$/min	39,536	39,562	39,599	39,446
Hg Conc., µg/dNm^3 at 3% O$_2$	9.67	4.47	3.81	2.58
Hg, µlb/hr	50,526	23,371	19,939	13,450
Hg				
Coal, µlb/hr	45,684	40,512	46,110	50,160
Koppers Ash, µlb/hr	784	3504	2940	3339
LC Ash, µlb/hr	112	10,388	25,817	35,686
Scrubber, µlb/hr	10,305	5429	7295	8418
Stack, µlb/hr	44,099	17,620	8059	5682
ID Fan Out, µlb/hr	50,526	23,371	19,939	13,450
Balance (O/I)				
Coal to Stack	121.0	91.2	95.7	105.9
Coal to ID Fan Out	112.6	92.0	105.6	104.6

Table J-2. HAP Baseline Mass Balance Data

Baseline	As	Be	Cd	Co	Cr	Mn	Ni	Pb	Sb	Se
SF10, lb/hr	0	0	0	0	0	0	0	0	0	0
SB24, lb/hr	0	0	0	0	0	0	0	0	0	0
Net MW	700	700	700	700	700	700	700	700	700	700
Coal Feed Rate, tons/hr	440	440	440	440	440	440	440	440	440	440
% Ash	3.66	3.66	3.66	3.66	3.66	3.66	3.66	3.66	3.66	3.66
Fly Ash Split	75	75	75	75	75	75	75	75	75	75
Bottom Ash Split	25	25	25	25	25	25	25	25	25	25
Coal, lb/hr	846,000	846,000	846,000	846,000	846,000	846,000	846,000	846,000	846,000	846,000
HAP Conc., ppm	**0.49**	**0.11**	**0.04**	**1.40**	**2.69**	**25.16**	**1.94**	**1.43**	**0.08**	**0.44**
HAP, µlb/hr	**410,711.3**	**95,710.31023**	**29,627.19**	**1,188,264**	**2,276,279.526**	**21,285,862**	**1,643,772**	**120,7086**	**68,432.95**	**369,753.7**
Total Ash, lb/hr	30,963.6	30,963.6	30,963.6	30,963.6	30,963.6	30,963.6	30,963.6	30,963.6	30,963.6	30,963.6
Fly Ash, lb/hr	23,223	23,223	23,223	23,223	23,223	23,223	23,223	23,223	23,223	23,223
SEA, lb/hr	0	0	0	0	0	0	0	0	0	0
Koppers										
Efficiency, %	85.7	85.7	85.7	85.7	85.7	85.7	85.7	85.7	85.7	85.7
Ash Collected, lb/hr	19,902	19,902	19,902	19,902	19,902	19,902	19,902	19,902	19,902	19,902
HAP Conc., ppm	**13.6**	**3.1**	**1.0**	**25.0**	**68.7**	**644.0**	**54.7**	**35.5**	**2.2**	**14.6**
HAP, µlb/hr	**269,670**	**61,708**	**20,480**	**497,666**	**1,366,271**	**12,817,095**	**1,088,828**	**707,434**	**44,655**	**291,426**
Sorbent, lb/hr	0	0	0	0	0	0	0	0	0	0
Ash Entering LC, lb/hr	3321	3321	3321	3321	3321	3321	3321	3321	3321	3321
LC										
Efficiency, %	95.1	95.1	95.1	95.1	95.1	95.1	95.1	95.1	95.1	95.1
Ash Collected, lb/hr	3158	3158	3158	3158	3158	3158	3158	3158	3158	3158
HAP Conc., ppm	**24.6**	**3.6**	**1.2**	**26.3**	**79.8**	**659.0**	**62.6**	**47.0**	**3.3**	**31.4**
HAP, µlb/hr	**77,532**	**11,293**	**3903**	**83,188**	**252,037**	**2,081,345**	**197,819**	**148,552**	**10,336**	**99,208**
Overall Eff., %	99.3	99.3	99.3	99.3	99.3	99.3	99.3	99.3	99.3	99.3

* Hazardous air pollutants.

Continued…

Table J-2. HAP Baseline Mass Balance Data (continued)

Baseline	As	Be	Cd	Co	Cr	Mn	Ni	Pb	Sb	Se
Scrubber										
Reagent Feed, lb/hr	25,507	25,507	25,507	25,507	25,507	25,507	25,507	25,507	25,507	25,507
% Solids, %	23.9	23.9	23.9	23.9	23.9	23.9	23.9	23.9	23.9	23.9
Solids In, lb/hr	6088	6088	6088	6088	6088	6088	6088	6088	6088	6088
Solids Out, lb/hr	7573	7573	7573	7573	7573	7573	7573	7573	7573	7573
HAP Reagent Feed Solid, ppm	4.95	0.20	0.20	7.14	16.05	52.40	29.90	5.42	0.65	1.64
HAP Conc., ppm	**3.00**	**0.20**	**0.20**	**1.01**	**4.15**	**6.52**	**8.28**	**2.62**	**0.15**	**2.93**
HAP, µlb/hr	**−7415**	**297**	**297**	**−35,817**	**−66,279**	**−269,618**	**−119,316**	**−13,154**	**−2821**	**12,250**
Stack										
Flow, dNm^3 at 3% O$_2$/min	39,536	39,536	39,536	39,536	39,536	39,536	39,536	39,536	39,536	39,536
HAP Conc., µg/dNm^3 at 3% O$_2$	**0.00**	**0.00**	**0.00**	**0.05**	**1.42**	**4.25**	**1.17**	**0.58**	**0.01**	**0.51**
Hg, µlb/hr	**0**	**0**	**0**	**261**	**7419**	**22,206**	**6113**	**3030**	**52**	**2665**
ID Fan Out										
Flow, dNm^3 at 3% O$_2$/min	39,536	39,536	39,536	39,536	39,536	39,536	39,536	39,536	39,536	39,536
HAP Conc., µg/dNm^3 at 3% O$_2$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
HAP, µlb/hr	0	0	0	0	0	0	0	0	0	0
HAP Balance (estimated HAP flows)										
Coal, µlb/hr	410,711.3	95,710.31023	29,627.19	1,188,264	2,276,279.526	21,285,862	1,643,772	1,207,086	68,432.95	369,753.7
Koppers Ash, µlb/hr	269,670	61,708	20,480	497,666	1,366,271	12,817,095	1,088,828	707,434	44,655	291,426
LC Ash, µlb/hr	77,532	11,293	3903	83,188	252,037	2,081,345	197,819	148,552	10,336	99,208
Scrubber, µlb/hr	−7415	297	297	−35,817	−66,279	−269,618	−119,316	−13,154	−2821	122,052
Stack, µlb/hr	0	0	0	261	7419	22206	6113	3030	52	2665
ID Fan Out, µlb/hr	0	0	0	0	0	0	0	0	0	0
Balance (O/I)										
Coal to Stack	82.7	76.6	83.3	45.9	68.5	68.8	71.4	70.1	76.3	109.7
Coal to ID Fan Out	–	–	–	–	–	–	–	–	–	–

Table J-3. HAP SF10–SB24 ET1 Mass Balance Data

SF10–SB24 ET1	As	Be	Cd	Co	Cr	Mn	Ni	Pb	Sb	Se
SF10, lb/hr	20	20	20	20	20	20	20	20	20	20
SB24, lb/hr	50	50	50	50	50	50	50	50	50	50
Net MW	700	700	700	700	700	700	700	700	700	700
Coal Feed Rate, tons/hr	440	440	440	440	440	440	440	440	440	440
% Ash	3.47	3.47	3.47	3.47	3.47	3.47	3.47	3.47	3.47	3.47
Fly Ash Split	75	75	75	75	75	75	75	75	75	75
Bottom Ash Split	25	25	25	25	25	25	25	25	25	25
Coal, lb/hr	880,000	880,000	880,000	880,000	880,000	880,000	880,000	880,000	880,000	880,000
HAP Conc., ppm	0.42	0.11	0.03	1.30	2.58	22.48	1.81	1.38	0.08	0.43
HAP, µlb/hr	371,690.8	98,087.97	29,591.1	114,6592	226,8506	19,779,022	1,592,600	1,216,043	73,474.32	378,585
Total Ash, lb/hr	30,536	30,536	30,536	30,536	30,536	30,536	30,536	30,536	30,536	30,536
Fly Ash, lb/hr	22,902	22,902	22,902	22,902	22,902	22,902	22,902	22,902	22,902	22,902
SEA, lb/hr	20	20	20	20	20	20	20	20	20	20
Koppers										
Efficiency, %	85.7	85.7	85.7	85.7	85.7	85.7	85.7	85.7	85.7	85.7
Ash Collected, lb/hr	19,644	19,644	19,644	19,644	19,644	19,644	19,644	19,644	19,644	19,644
HAP Conc., ppm	17.3	3.1	1.4	24.1	73.7	621.6	56.9	38.8	2.6	17.6
HAP, µlb/hr	340,335	60,279	26,914	473,196	1,447,823	12,210,114	1,118,290	761,885	50,599	346,451
Sorbent, lb/hr	50	50	50	50	50	50	50	50	50	50
Ash Pre-LC, lb/hr	3328	3328	3328	3328	3328	3328	3328	3328	3328	3328
LC										
Efficiency, %	95.1	95.1	95.1	95.1	95.1	95.1	95.1	95.1	95.1	95.1
Ash Collected, lb/hr	3165	3165	3165	3165	3165	3165	3165	3165	3165	3165
HAP Conc., ppm	26.5	3.4	1.3	25.5	82.2	584.7	63.6	48.2	3.4	39.2
HAP, µlb/hr	83,708	10,835	4155	80,842	260,013	1,850,513	201,230	152,678	10,873	123,969
Overall Eff., %	99.3	99.3	99.3	99.3	99.3	99.3	99.3	99.3	99.3	99.3

Continued…

Table J-3. HAPs SF10–SB24 ET1 Mass Balance Data (continued)

SF10–SB24 ET1	As	Be	Cd	Co	Cr	Mn	Ni	Pb	Sb	Se
Scrubber										
Reagent Feed, lb/hr	23,813	23,813	23,813	23,813	23,813	23,813	23,813	23,813	23,813	23,813
% Solids, %	24.4	24.4	24.4	24.4	24.4	24.4	24.4	24.4	24.4	24.4
Solids In, lb/hr	5810	5810	5810	5810	5810	5810	5810	5810	5810	5810
Solids Out, lb/hr	7228	7228	7228	7228	7228	7228	7228	7228	7228	7228
HAP Reagent Feed	5.24	0.20	0.20	7.61	16.80	52.60	32.70	4.93	0.61	2.47
HAP Conc., ppm	2.56	0.20	0.20	1.00	3.64	5.22	8.27	2.64	0.14	2.68
HAP, µlb/hr	−11,942	284	284	−36,989	−71,304	−267,895	−130,223	−9563	−2532	5020
Stack										
Flow, dNm^3 at 3%	39,562	39,562	39,562	39,562	39,562	39,562	39,562	39,562	39,562	39,562
HAP Conc., µg/dNm^3	0.00	0.00	0.00	0.08	0.75	3.86	1.18	0.66	0.02	0.36
HAP, µlb/hr	0	0	0	424	3921	20,182	6170	3451	105	1882
ID Fan Out										
Flow, dNm^3 at 3%	39,562	39,562	39,562	39,562	39,562	39,562	39,562	39,562	39,562	39,562
HAP Conc., µg/dNm^3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
HAP, µlb/hr	0	0	0	0	0	0	0	0	0	0
HAP Balance (estimated HAP flows)										
Coal, µlb/hr	371,690.8	98,087.9	29,591.1	1,146,592	2,268,506	19,779,022	1,592,600	1,216,043	73,474.3	378,585
Koppers Ash, µlb/hr	340,335	60,279	26,914	473,196	1,447,823	12,210,114	1,118,290	761,885	50,599	346,451
LC Ash, µlb/hr	83,708	10,835	4155	80,842	260,013	1,850,513	201,230	152,678	10,873	123,969
Scrubber, µlb/hr	−11,942	284	284	−36,989	−71,304	−267,895	−130,223	−9563	−2532	5020
Stack, µlb/hr	0	0	0	424	3921	20,182	6170	3451	105	1882
ID Fan Out, µlb/hr	0	0	0	0	0	0	0	0	0	0
Balance (O/I)										
Coal to Stk	110.9	72.8	106.0	45.1	72.3	69.8	75.1	74.7	80.4	126.1
Coal to ID Fan Out	–	–	–	–	–	–	–	–	–	–

APPENDIX K

LEACHING RESULTS

LEACHING RESULTS

LEACHING METHODS

Coal combustion product (CCP) samples from both the east (injection side) and west (baseline side) electrostatic precipitators (ESPs) was evaluated for the leachability of select constituents using the “Integrated Framework for Evaluating Leaching in Waste Management and Utilization of Secondary Materials” (Kosson et al., 2002) method, which has been adopted by the U.S. Environmental Protection Agency (EPA) for the evaluation of CCPs. The integrated framework has been referred to as the “three-tier leaching protocol,” and a number of the tests within the three tiers were used in this study. The resulting leachate samples were evaluated for six trace elements (arsenic, cadmium, chromium, mercury, nickel, and selenium), three halogens (bromide, chloride, and fluoride), and sulfur oxide compounds as sulfates.

The three-tier leaching protocol involves several discrete procedures. The procedures in Tier 1 are pH001.0 Titration Pretest and AV002.1 Availability Test; Tier 2 includes SR002.1 Leachability A and SR003.1 Leachability B; and MT002.1 Mass Transfer from granular materials is Tier 3. Based on work performed by EPA, the procedures performed on the CCPs in this project were the titration pretest from Tier 1 and the Leachability A and B tests from Tier 2 (Sanchez et al., 2006). The titration pretest was used to determine the amount of acid or base solution needed to alter the natural pH of the CCPs over a pH range of 2 to 12. The natural pH of each CCP was determined at a 100:1 liquid-to-solid (LS) ratio. Aliquots of 1 N KOH were added sequentially to increase the pH of the solution to pH 12, with the pH monitored and recorded after each addition. The pH was decreased in the same manner using 2 N HNO_3. Based on the acid and base aliquots and the corresponding pH values, a titration curve was plotted to generate a table of acid or base addition rates for the Tier 2 SR002.1 Leachability A procedure. This first Tier 2 procedure consists of leachate samples at eleven target pH levels of 2–12 at a LS ratio of 10:1 using distilled, deionized water plus the calculated amount of 1 N KOH or 2 N HNO_3. For this project, a sample was also leached without acid or base addition. The Tier 2 SR003.1 Leachability B procedure consists of leaching the sample at five LS ratios including 10:1, 5:1, 2:1, 1:1, and 0.5:1. Each sample was rotated over a 48-hour period, with end-over-end agitation at approximately 30 rpm for each Tier 2 procedure, as applicable. Exceptions to test procedures performed are noted in the test results.

For each of the leaching procedures, the solids were filtered from the leaching solution through a 0.45-µm filter. Prior to filtering, some leaching solutions were centrifuged to aid in the filtering process. The pH of the resulting leachate was measured, and the leachate was preserved with HCl for mercury determination, with HNO_3 for determination of other trace elements, and was unpreserved for the halogens and sulfate. Table K-1 provides the analysis methods used for each of the analytes.

Table K-1. Analysis Methods Used for Each Analyte

Analyte	Method	Title	Reporting limit, mg/L
Antimony	EPA SW846 Method 6020A	Inductively Coupled Plasma Atomic Emission Spectroscopy	0.005
Arsenic	EPA SW846 Method 7010	Graphite Furnace Atomic Absorption Spectrometry	0.004
Beryllium	EPA SW846 Method 6020A	Inductively Coupled Plasma Atomic Emission Spectroscopy	0.0002
Bromide	EPA Method 300.0	Determination of Inorganic Anions by Ion Chromatography	1.0
Cadmium	EPA SW846 Method 6020A	Inductively Coupled Plasma Mass Spectrometry	0.0005
Chromium	EPA SW846 Method 6020A	Inductively Coupled Plasma Mass Spectrometry	0.001
Chloride	EPA Method 300.0	Determination of Inorganic Anions by Ion Chromatography	1.0
Cobalt	EPA SW846 Method 6020A	Inductively Coupled Plasma Atomic Emission Spectroscopy	0.001
Fluoride	EPA Method 300.0	Determination of Inorganic Anions by Ion Chromatography	1.0
Lead	EPA SW846 Method 6020A	Inductively Coupled Plasma Atomic Emission Spectroscopy	0.01
Manganese	EPA SW846 Method 6020A	Inductively Coupled Plasma Atomic Emission Spectroscopy	0.05
Mercury	Modified EPA Method 245.1	Cold-Vapor Atomic Absorption Spectrometry	0.00005
Nickel	EPA SW846 Method 6020A	Inductively Coupled Plasma Mass Spectrometry	0.001
Selenium	EPA SW846 Method 6020A	Inductively Coupled Plasma Mass Spectrometry	0.002
Sulfate	EPA Method 300.0	Determination of Inorganic Anions by Ion Chromatography	1.0

LEACHATE RESULTS

Tier 2 Leachability A Procedure Results

CCP samples were collected during the baseline and ET1 test periods. The Tier 2 Leachability A procedure determines how pH affects the leachate properties of the CCP. Figure K-1 displays the difference between the target pH and the leachate pH. Each sample is mixed with a leachant calculated to alter the leaching solution to the target pH, and allowed to leach for 48 hours, after which the final leachate pH is measured. The final filtered leachate solution pH value was greater than the target pH for every leachate, especially as the target pH value decreased. As more acid was added to the leachant, the leachate pH remained in the 11–9.5 range for the ET samples until the target pH was 4. The baseline sample saw a significant change in leachate pH at a target pH of 9. The deviation from the target pH demonstrates the buffering

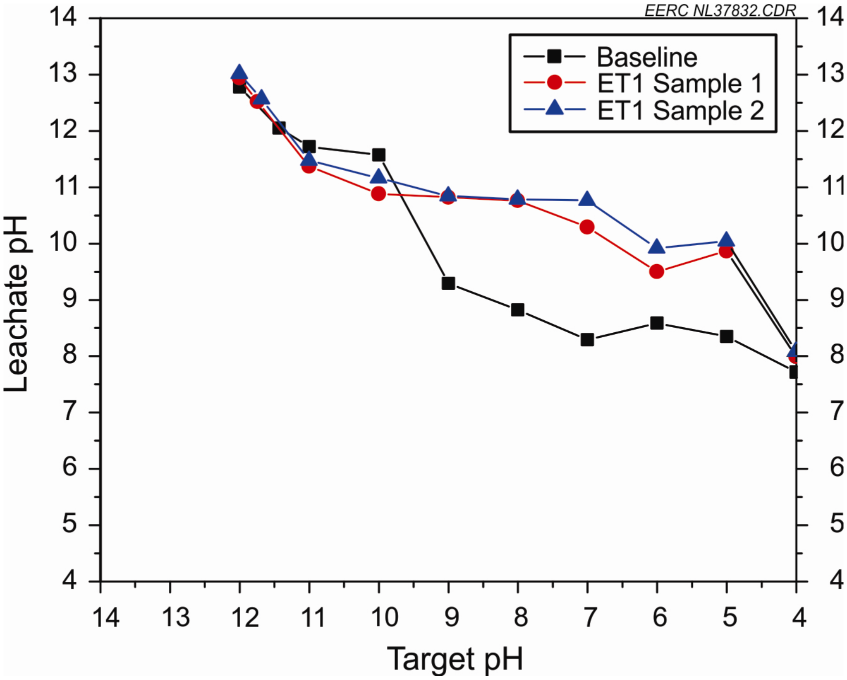


Figure K-1. Comparison between the target pH and leachate pH.

capacity of the CCP. This trend was consistent for all of the CCP samples, including the "natural-pH" or unaltered CCP–liquid sample. It should be noted that the target pH 2 was unachievable for the SF10-SB24 injection side CCP sample.

The leachate hazardous air pollutant (HAP) results for baseline and ET1 test conditions are presented in Figures K-2a–c. Figure K-2a represents the baseline test condition and Figures K-2b and 2c represent ET1 test conditions. During ET1, the SF10 and SB24 injection rates were 20 and 50 lb/hr, respectively. The data show that most of the HAP elements leach out at very low concentrations for both the baseline and ET1 samples. The four elements that leach out at higher concentrations are Cr, Mn, Ni, and Se. Mn leaches out in both the baseline and ET1 samples at the most acidic pH. The Mn leachate concentration is much lower for both ET1 samples compared to the baseline sample. The Cr and Se leachate concentrations are generally higher at the most basic and acidic ends of the leachate pH. The Ni leachate concentration increased as the leachate pH became more acidic. The leachate concentrations of the Cr, Ni, and Se elements were similar for both the baseline and ET1 samples. All of the leachate concentrations across the entire pH range are well below the allowable toxicity characteristic leaching procedure (TCLP) limits.

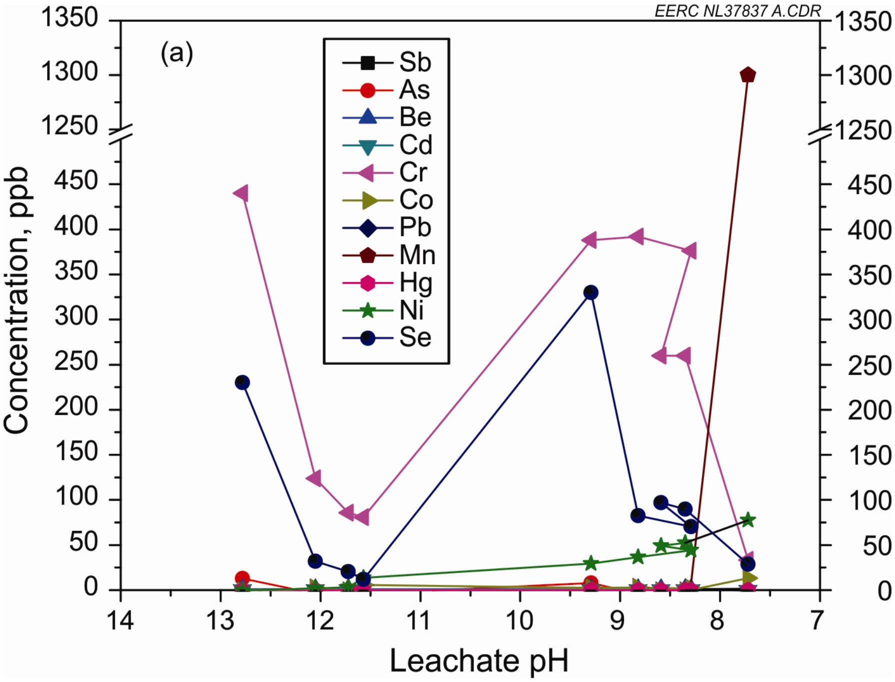


Figure K-2a. HAP element baseline leachate data. It should be noted that the final two low pH values could not be attained for the sample.

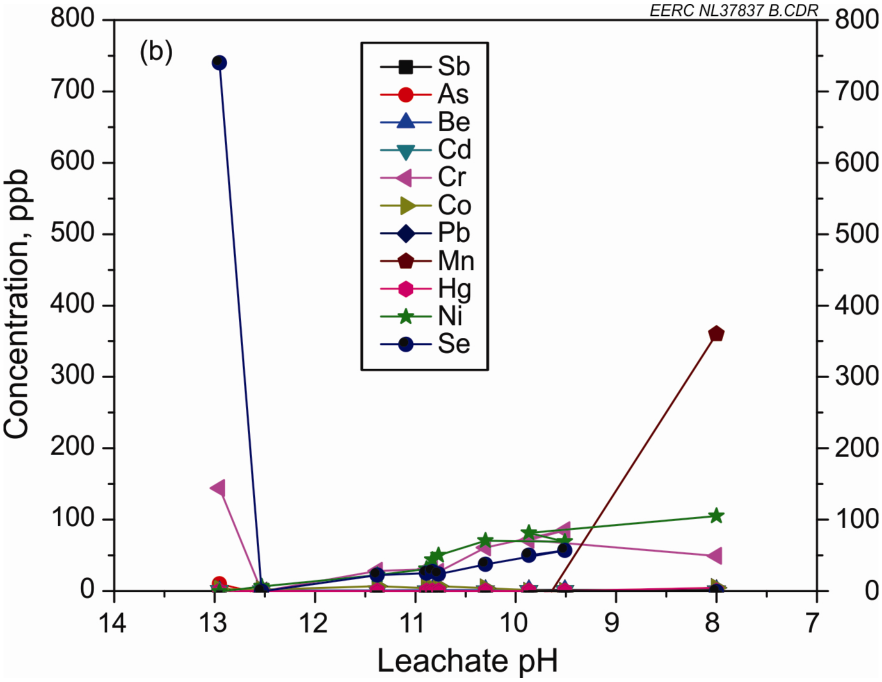
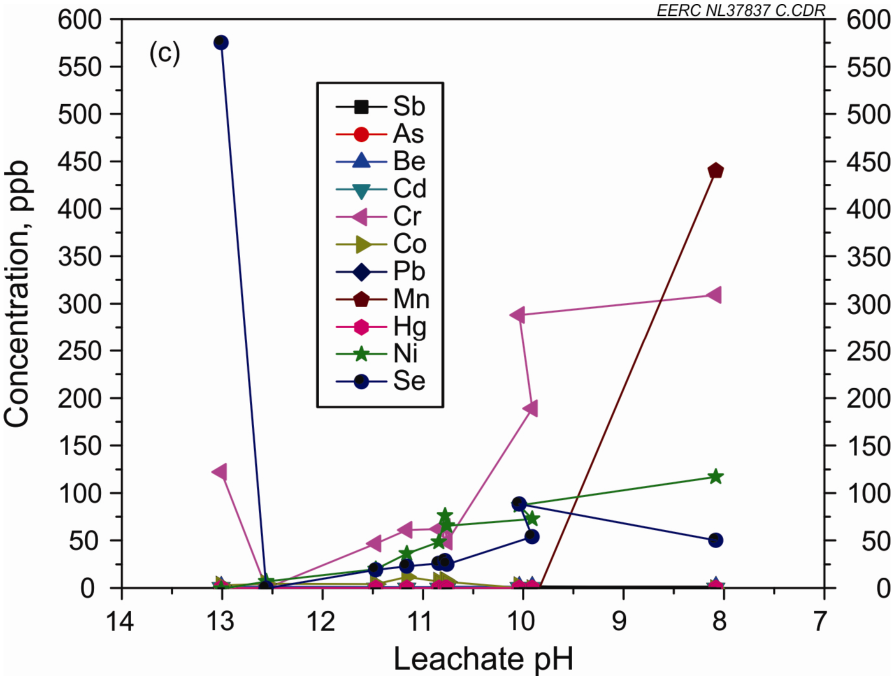


Figure K-2b. ETI-sample 1 HAP element leachate data. It should be noted that the final two low pH values could not be attained for the sample.



Figures K-2c. HAP element ETI-sample 2 leachate data. It should be noted that the final two low pH values could not be attained for the sample. The scales differ on each plot to provide adequate data resolution.

In addition to the HAP elements, Br, Cl, F, and SO_4 concentrations were also determined in the baseline and ET1 leachate samples. Figures K-3a–c display the leachate results for Br, Cl, F, and SO_4 for the baseline and two ET1 CCP samples, respectively. Of the four nonmetals, only SO_4 leached out in significant concentrations in both the baseline and ET1 samples. The SO_4 concentration was much higher in the baseline sample than the ET1 samples.

Figure K-4 plots the total percentage of each HAP element that leached out of the baseline and ET1 CCP samples. The figure shows that the percentages of each HAP element that leach out of the CCP samples are very low, with most of the HAP elements having less than 1% leach out of the CCP samples. Cr and Se were the two elements that leached out the most, but the concentrations were still <5% of the total amount in the CCP sample. This shows that the majority of the HAP elements remain in the CCP samples and do not leach out across the tested pH range.

Tier 2 Leachability B Procedure Results

In addition to Leachability A tests, Leachability B (liquid-to-solid ratio) tests were also performed on the CCP samples. In the Tier 2 Leachability B tests, the pH is left at the "natural" pH, and the LS ratio is varied. By varying the LS ratio, the Tier 2 Leachability B tests determine

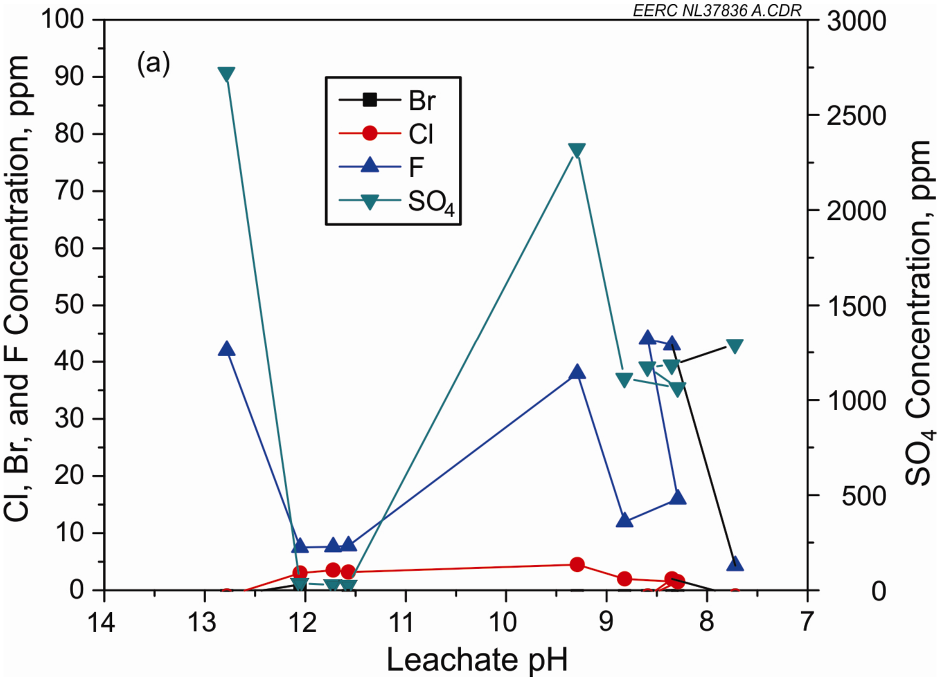


Figure K-3a. Baseline Cl, Br, F, and SO_4 leachate data. It should be noted that the final two low pH values could not be attained for the sample.

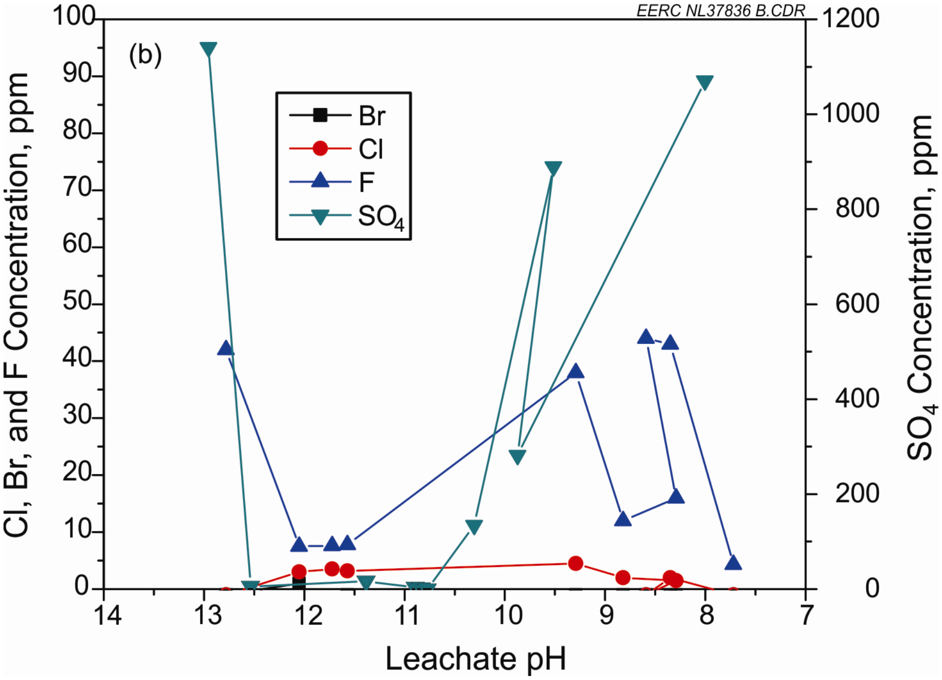
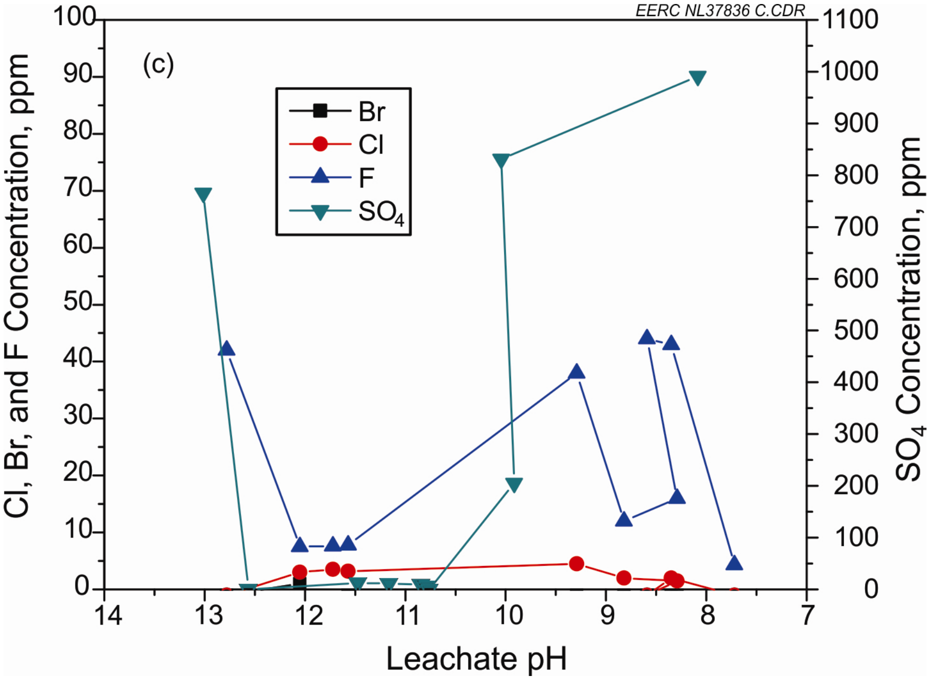


Figure K-3b. ETI-sample 1 Cl, Br, F, and SO_4 leachate data. It should be noted that the final two low pH values could not be attained for the sample.



Figures K-3c. ETI-sample 2 Br, Cl, , and SO_4 leachate data. It should be noted that the final two low pH levels could not be attained for the samples. The scales differ on each plot to provide adequate data resolution.

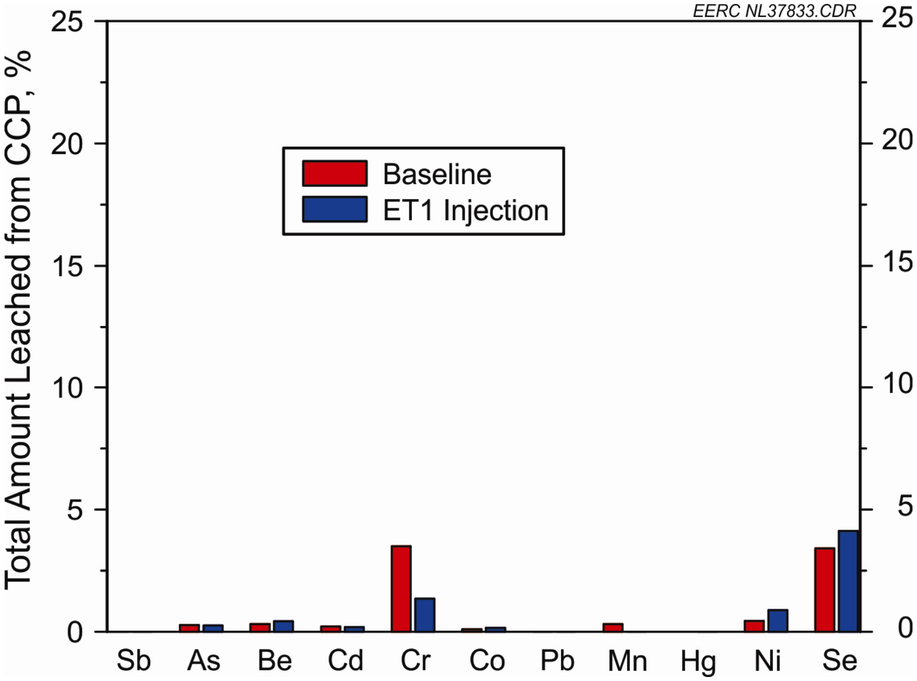


Figure K-4. Percentage of each HAP element that leached out of the baseline and ET1 CCP samples.

how the CCP hydration characteristics affect the analytes that leach into the solution. The CCP hydration characteristics did not allow for the 1:1 and 0.5 LS ratio tests to be performed; therefore, only the 2:1, 5:1, 10:1, and 20:1 LS ratio tests were performed for the samples. The 2:1 LS ratio was only performed on the baseline sample.

Figures K-5a–c show the LS ratio HAP element leachate tests for the baseline and ET1 CCP samples. The baseline leachate data in Figure K-5a show that only Cr and Se show slight concentration changes at the different LS ratios. For both of these elements, the leachate concentration is greater at lower LS ratios. This trend is not observed in the ET1 data. The other HAP elements do not exhibit any significant changes at the different LS ratios.

The effects that the LS ratio has on nonmetal species of interest were also examined. Figures K-6a–c show the LS ratio data for Cl, Br, F, and SO_4 for the baseline and ET1 CCP samples. The trends for Cl, Br, F, and SO_4 do not significantly increase or decrease in either the baseline or ET1 samples which shows that the LS ratio does not impact the leaching properties of these select nonmetals.

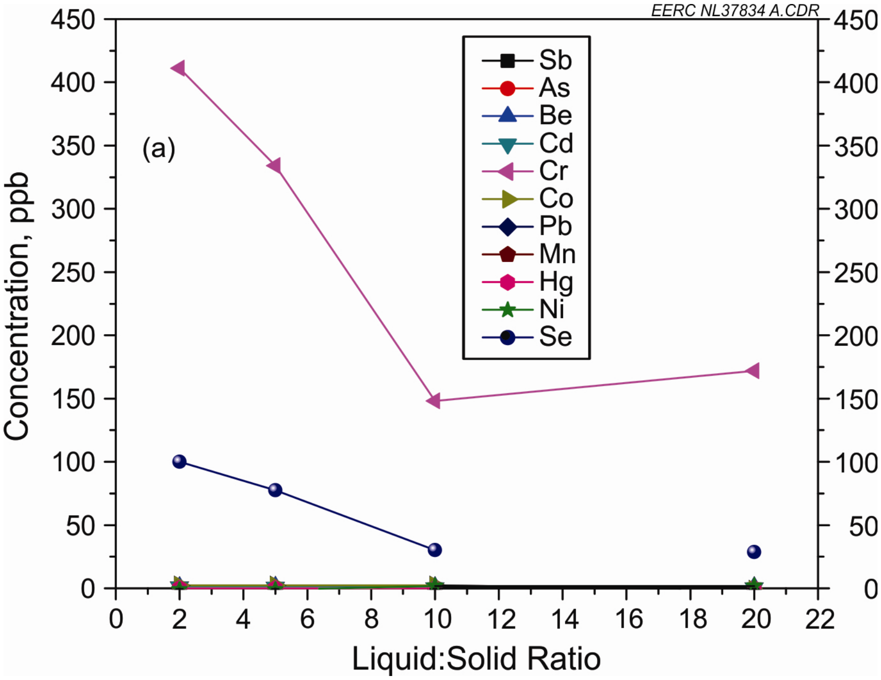


Figure K-5a. Baseline HAP LS ration leachate data.

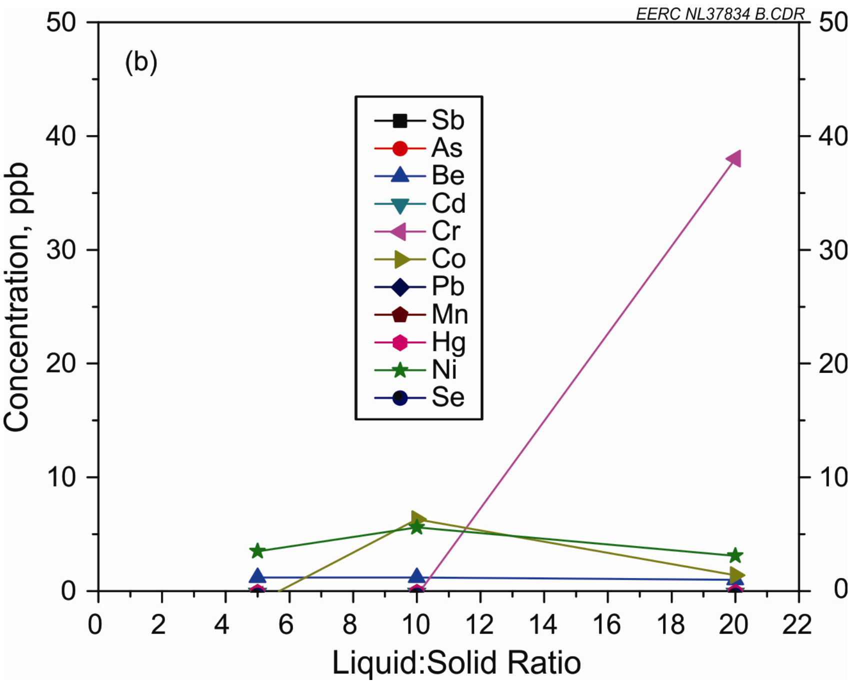
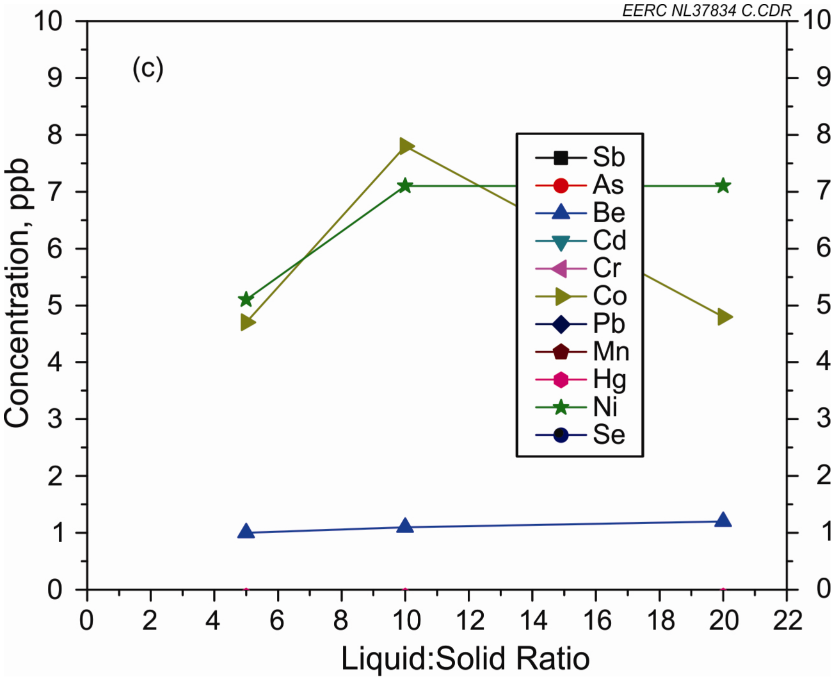


Figure K-5b. ETI-sample 1 HAP LS ratio leachate data.



Figures K-5c. HAP ET1-sample 2 LS ratio leachate data. The scales differ on each plot to provide adequate data resolution.

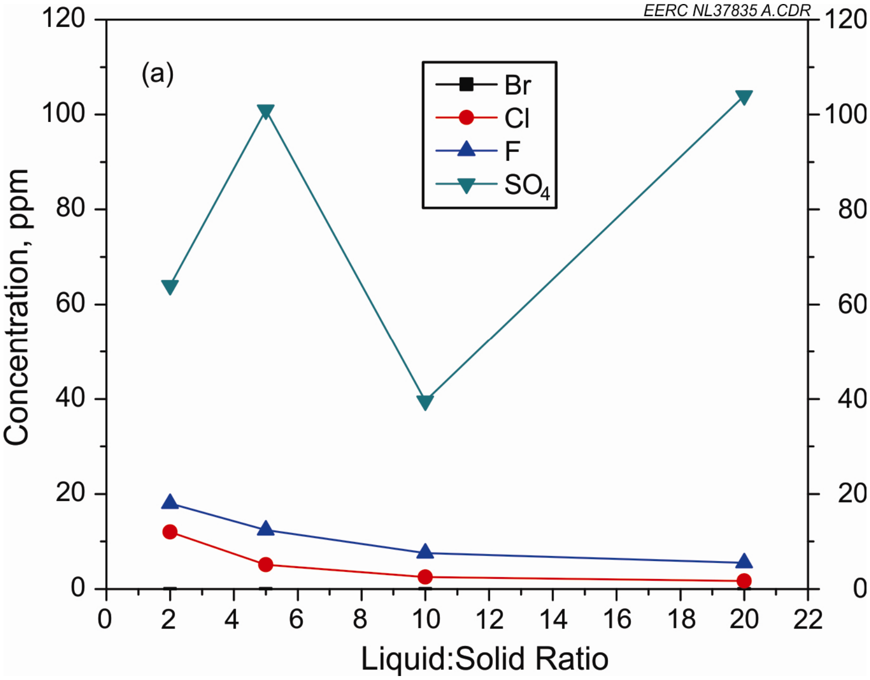


Figure K-6a. Baseline Cl, Br, F, and SO_4 LS ratio data.

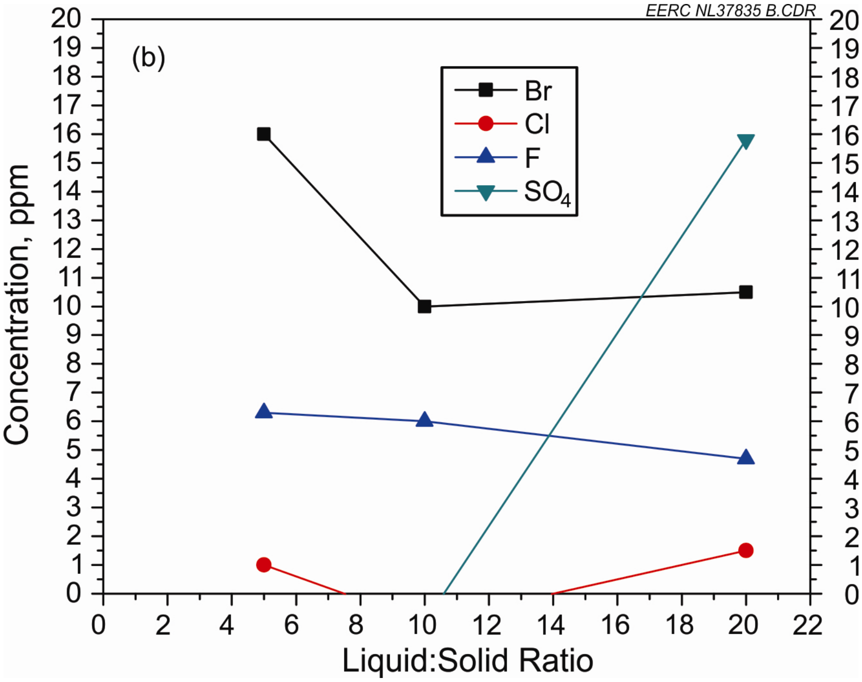
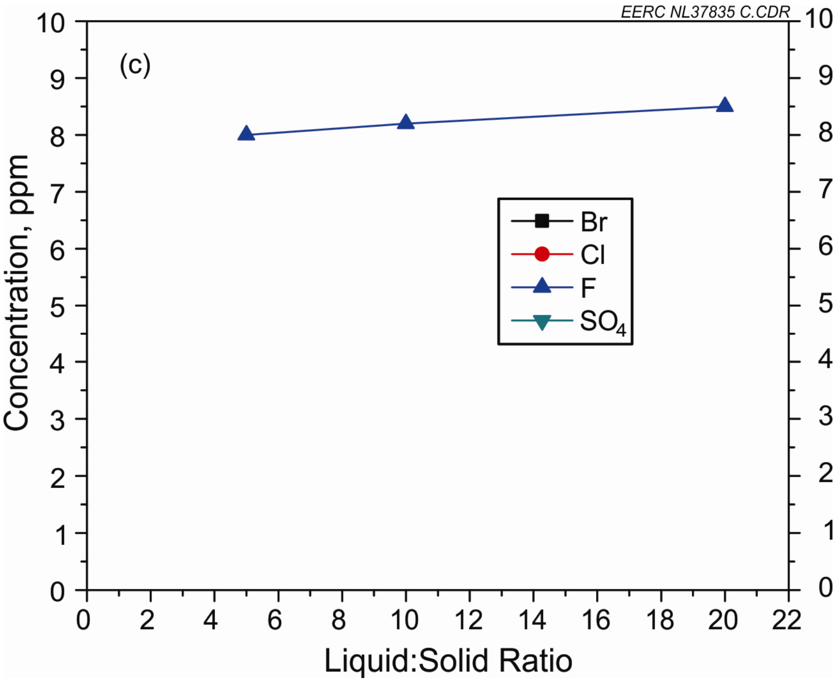


Figure K-6b. ETI-sample 1 Cl, Br, F, and SO_4 LS ratio data.



Figures K-6c. ETI-sample 2 Cl, Br, F, and SO_4 LS ratio data. The scales differ on each plot to provide adequate data resolution.

References

Kosson, D.S.; van der Sloot, H.A.; Sanchez, F.; Garrabrants, A.C. An Integrated Framework for Evaluating Leaching in Waste Management and Utilization of Secondary Materials. *Environ. Eng. Sci.* **2002**, *19* (3), 159–203.

Sanchez, F.; Keeney, R.; Kosson, D.; Delapp, R. *Characterization of Mercury-Enriched Coal Combustion Residues from Electric Utilities Using Enhanced Sorbents for Mercury Control*; U.S. Environmental Protection Agency EPA-600/R-06/008, Feb 2006.

APPENDIX D

FULL-SCALE MERCURY CONTROL DEMONSTRATIONS: ICR SAMPLING WITH MERCURY CONTROL

FULL-SCALE MERCURY CONTROL DEMONSTRATIONS: ICR SAMPLING WITH MERCURY CONTROL

Final Report

(for the period of June 29, 2009, through February 28, 2011)

Prepared for:

AAD Document Control

U.S. Department of Energy
National Energy Technology Laboratory
626 Cochrans Mill Road
PO Box 10940, MS 921-107
Pittsburgh, PA 15236-0940

Cooperative Agreement No.: DE-FC26-06NT42775

Prepared by:

Jason D. Laumb
John P. Kay
Nicholas B. Lentz

Energy & Environmental Research Center
University of North Dakota
15 North 23rd Street, Stop 9018
Grand Forks, ND 58202-9018

2011-EERC-02-06

February 2011

DISCLAIMER

This report is available to the public from the National Technical Information Service, U.S. Department of Commerce, 5285 Port Royal Road, Springfield, VA 22161; phone orders accepted at (703) 487-4650.

EERC DISCLAIMER

LEGAL NOTICE This research report was prepared by the Energy & Environmental Research Center (EERC), an agency of the University of North Dakota, as an account of work sponsored by the U.S. Department of Energy National Energy Technology Laboratory and Otter Tail Power Company. Because of the research nature of the work performed, neither the EERC nor any of its employees makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement or recommendation by the EERC.

FULL-SCALE MERCURY CONTROL DEMONSTRATIONS: ICR SAMPLING WITH MERCURY CONTROL

ABSTRACT

The U.S. Environmental Protection Agency (EPA) issued an information collection request (ICR) for all coal- and oil-fired utility units of >25MWe. This information will assist in the formation of a maximum achievable control technology standard for mercury. Otter Tail Power was not only to provide the required general facility information, fuel analyses, and emission data but was also randomly selected to provide data on all hazardous air pollutants (HAPs) groups as defined in ICR Part III. This project provided the opportunity to assist Otter Tail Power with the ICR requirements and collect data on the effect of a mercury control technology on the emissions of selected HAPs.

The Energy & Environmental Research Center successfully completed the ICR sampling required by EPA, and the results are presented. The data were submitted to EPA August 2010. The mercury removal technology selected by Otter Tail was a sorbent/additive technology provided by Grünergy Technologies. Grünergy technology entailed injecting an additive in the boiler while simultaneously injecting a sorbent upstream of the air heater. Parametric tests were carried out with the technology over 2 days. A rate was selected to provide 80%–85% mercury reduction, which held while the repeat sampling for selected HAPs was conducted. Parametric testing indicated that 85% mercury removal could be achieved with a sorbent/additive injection rate of 2.35/0.47 lb/Macf, respectively, and greater than 90% mercury removal could be gained with rates above 4.27/0.85 lb/Macf.

HAP sampling was compared to identical sampling methods carried out during the ICR portion of testing. The testing indicated that the majority of metallic HAPs did not change except for beryllium and cobalt, which did decrease, and selenium, which greatly increased. There was no effect on hydrogen chloride emissions, but hydrogen fluoride emissions also greatly increased. Total filterable particulate and filterable $PM_{2.5}$ loading slightly decreased, but the inorganic and organic condensables increased.

Partitioning of the particulate and gaseous phase contributions of these sampling techniques were not evaluated; however, further work needs to be done to evaluate them. This project also developed results that were highly varied from one test run to another for each parameter. Further testing with a much more intense sampling strategy should be employed to better reduce uncertainty and better analyze trends.

TABLE OF CONTENTS

LIST OF FIGURES ii

LIST OF TABLES iii

EXECUTIVE SUMMARY iv

INTRODUCTION 1
  Acid Gas HAPs 3
  Dioxin/Furan Organic HAPs 3
  Non-Dioxin/Furan Organic HAPs 3
  Mercury and Other Nonmercury Metallic HAPs 3
  Other 3
  Status of HAPs Work 4
  Sorbents and Additives 7
  ICR Testing at Hoot Lake Plant 8

GOALS AND OBJECTIVES 8

DESCRIPTION OF TEST MATERIAL 8

DESCRIPTION OF TEST UNIT, SAMPLING LOCATIONS, AND EQUIPMENT 9
  Gas-Sampling Locations 9
  SEA Injection Location 10
  Upstream of Air Heater Injection Location 10
  Injection Equipment 10
  Sampling Methods 12

TEST COAL 13

TEST PLAN 14
  CEM and Sorbent Trap Sampling 14

RESULTS AND DISCUSSION 15
  ICR Sampling 15
  Sorbent/Additive Injection 27

CONCLUSIONS 34

REFERENCES 34

LIST OF FIGURES

1 Chromium emissions and partitioning 5

2 Lead emissions and partitioning 5

3 Nickel emissions and partitioning 6

4 Selenium emissions and partitioning 6

5 Schematic of the test unit showing injection and sampling locations 9

6 Port locations for sampling 10

7 Modified furnace door showing injection lance installed at the northwestern corner of the boiler, fourth-floor level 11

8 Sorbent injection lances located upstream of the AH 11

9 Comparison of day-to-day mercury concentration in the test coal 16

10 Stack percent mercury removals as a function of parametric SF10–SB24 injection rates 29

11 Hourly stack mercury removals during the SF10–SB24 extended test 30

12 Comparison of particulate data from ICR sampling and sorbent/additive sampling 31

13 EPA Method 26 and selected EPA Method 29 results 33

14 EPA Method 29 results comparison 33

LIST OF TABLES

1 Hg Control Projects Providing HAP Data 7

2 Sorbent/Additive Used During Testing 9

3 Test Matrix for ICR Sampling at Hoot Lake Power Plant Unit 2 12

4 Test Schedule 14

5 Average Properties of Test Coal 16

6 Average Value for Each Run for Oxygen (O_2), Carbon Dioxide (CO_2), and Moisture (H_2O) 17

7 Carbon Monoxide (CO), Total Organic Compounds (TOCs), Methane (CH_4), and Formaldehyde Results 17

8 Speciated Semivolatile Organic HAP Results 18

9 Speciated Volatile Organic HAP Results 21

10 Results for HCl, HF, and HCN 23

11 Dixoin/Furan HAP Results 24

12 Particulate Matter Sampling Results 26

13 Mercury and Metallic HAP Sampling Results 26

14 Sorbent/Additive Injection Rates Used During Testing 28

15 Particulate Matter Sampling Results During Sorbent/Additive Injection 30

16 Results for HCl and HF During Sorbent/Additive Injection 31

17 Mercury and Metallic HAP Sampling Results During Sorbent/Additive Injection 32

FULL-SCALE MERCURY CONTROL DEMONSTRATIONS: ICR SAMPLING WITH MERCURY CONTROL

EXECUTIVE SUMMARY

With a maximum achievable control technology (MACT) standard for mercury looming on the horizon, the U.S. Environmental Protection Agency (EPA) has issued an information collection request (ICR) for all coal- and oil-fired utility units of >25MW$_e$ entitled “Information Collection Request for National Emission Standards for Hazardous Air Pollutants (NESHAP) for Coal- and Oil-Fired Electric Utility Steam-Generating Units.”

The ICR is divided into three parts:

- Part I – General Facility Information

  All facilities meeting Section 112(a)(8) definition shall report:

- Part II – Fuel Analyses and Emission Data

  All facilities randomly identified to perform stack testing shall report:

- Part III – Emission Test Data: Units identified for sampling under Part III will be required to sample for one or more of the following hazardous air pollutant (HAP) categories for coal-fired units:

  - Acid gas HAPs (e.g., HCl and HF)
  - Dioxin/furan organic HAPs
  - Non-dioxin/furan organic HAPs
  - Mercury and other nonmercury metallic HAPs
  - Other

The Otter Tail Power Company’s Hoot Lake Plant Unit 2 was one of 50 randomly selected plants by EPA to perform Part III emission data for all HAP groups except dioxin/furans. Hoot Lake Plant Unit 3 was one of the 50 randomly selected units to perform Part III emission data for dioxin/furans. After discussions, the EPA granted a request by Otter Tail Power to perform all sampling on Unit 2.

The cobenefits and impacts that mercury control will have on the complete power-generating system will become more important as MACT standards for all HAPs move forward. Work has been undertaken to begin collecting data on the effects of mercury control technologies, and EPA encouraged participating power plants to provide ICR data during mercury control injection but did not require it. Data have been collected through various projects and to date show that there is high variability in emissions, and most metallic HAP emissions appear to remain unchanged.

The goal of this project was to perform ICR sampling to meet the requirements of EPA and then repeat some of the sampling during the injection of a mercury reduction technology. These data will contribute to an immature database of generated information on the influence of sorbents on a unit's stack emission.

The mercury control technology was provided by Grünergy Technologies. Grünergy suggested that the best technology for Hoot Lake Unit 2 was a sorbent/additive combination denoted SB24 and SF10, respectively. The additive SF10 is injected into the boiler while simultaneously injecting the sorbent SB24 upstream of the air heater.

The Energy & Environmental Research Center (EERC) performed gas sampling at Hoot Lake Unit 2 from May 14 through May 27, 2010. Unit 2 is a 54-MW unit with a tangentially fired boiler fueled by Spring Creek subbituminous coal; particulate matter is controlled by a cold-side electrostatic precipitator (ESP). The EERC successfully completed the required sampling to meet EPA requirements and assisted Otter Tail Power in compiling the information into the EPA's Electronic Reporting Tool (ERT). The completed ERT data were submitted to EPA August 2010.

EERC staff returned to Hoot Lake June 7 through June 18, 2010, and performed parametric testing of Grünergy sorbent/additive technology and performed gas sampling of selected acid gas HAPs, metallic HAPs, and particulate. Mercury concentration of the flue gas at the outlet of the unit's ESP was measured with a mercury continuous emission monitor. Results of parametric injection tests were calculated on a coal-to-stack basis and relative reduction at the ESP outlet. Parametric tests indicated that 85% mercury removal could be obtained with sorbent/additive rates of 2.35/0.47 lb/Macf, respectively. To achieve greater than 90% removal will require sorbent/additive rates above 4.27/0.85 lb/Macf, respectively.

A mercury removal target of 80%–85% was selected for constant injection during flue gas sampling. The injection rate for sorbent/additive was 2.13/0.43 lb/Macf, respectively. Sampling using EPA Methods 26a, 29, and combined Other Test Method 27/28 for the collection of HAPs data was conducted over a 4-day period. The selected injection rate did maintain an average removal within the target range, but mercury concentration in the flue was variable.

Comparison of the data with the identical sampling conducted during the ICR portion of the project agreed with past work in that the resultant concentrations of HAPs were highly variable. Most of the metallic HAPs were unchanged except for beryllium and cobalt, which did decrease, and selenium, which actually increased concentration during sorbent/additive injection. Hydrogen fluoride concentration also increased. Total filterable particulate loading and filterable $PM_{2.5}$ decreased; however, inorganic and organic condensables increased.

Partitioning of the particulate and gaseous phase contributions of these sampling techniques were not evaluated in this project, but further work needs to be done to evaluate them. This project also developed results that were highly varied from one test run to another for each parameter. Further testing with a much more intense sampling strategy should be employed to better reduce uncertainty.

FULL-SCALE MERCURY CONTROL DEMONSTRATIONS: ICR SAMPLING WITH MERCURY CONTROL

INTRODUCTION

The U.S. Department of Energy National Energy Technology Laboratory (NETL) implemented a program focused on technology development and testing that would provide significant mercury reduction (90%). Over the past decade, several entities, including the Energy & Environmental Research Center (EERC), NETL, other research groups, technology providers, and electric generation companies have dedicated significant resources to work with industry and the federal government to study the fate and formation of mercury in coal-fired electric generation power plants, providing significant advances in understanding and developing control technologies. While advancements continue to be made, many significant challenges and questions remain, especially in light of the maximum achievable control technology (MACT) standard that is under development; new technologies and longer-term testing are vitally needed. The following critical issues must be addressed if broad application of the MACT standard is to occur:

- *Technology Challenges and Long-Term Testing of Mercury Control Technologies* – To date, only short-term, monthlong tests have been completed. While some technologies have shown promise, many issues remain unresolved, such as long-term performance, reemission, the impact of SO_3, balance-of-plant impacts, and possible unwanted (unknown) environmental consequences. Some of these impacts can only be understood and resolved by performing long-term tests, 9 to 18 months in duration.

- *Testing of Mercury Control Technologies on a Wide Variety of Plants and Coals (and coal blends)* – Issuance of the MACT standard will require that all 1200-plus coal-fired units in the United States apply mercury control technologies. To date, fewer than 10% have been tested and only to a limited degree. Consequently, many coal types, blends, and unit configurations have not been tested. This lack of data leads to uncertainty and will cause utilities major challenges as they try to determine what technologies will work best given their coals and individual unit configurations. Additionally, as more utilities purchase subbituminous coals or use opportunity coals such as low-rank coals, there is a continued need to determine how these coals perform in integrated gasification combined-cycle (IGCC) and oxygen-fired systems that may be deployed to address CO_2 concerns.

- *Development of Long-Term Mercury-Sampling and Analysis Protocols, Including Development and Testing of Continuous Mercury Measurement Systems and Verification Systems* – Robust systems that are reliable and economical are still needed, along with U.S. Environmental Protection Agency (EPA)-developed methods to certify and audit the monitors. For example, the MACT will likely require high levels of mercury control, resulting in the need to accurately measure mercury for compliance purposes at very low concentrations (less than 1 $\mu g/dNm^3$). To date, this has not been validated.

- *Evaluation of Beneficial or Negative Effects of Future Emission Control Systems (especially CO_2 capture technologies) on Mercury Control Requirements* – Many of the CO_2 technologies require extremely clean flue gas. Mercury is known to have a negative impact on many of these systems, and its impact on other systems is under investigation. As a result, increased levels of mercury and trace element control may be required to enable the use of CO_2 capture technologies.

- *Development and Testing of Multipollutant Control Technologies (including CO_2)* – Development and testing of new-generation multipollutant control devices must continue to provide more integrated and cost-effective solutions that address all pollutants of concern collectively rather than on a single-pollutant basis. Multipollutant technologies and their impact on advanced energy conversion systems using elevated pressures and temperatures must be tested to ensure system reliability and continued emission performance.

With a MACT standard for mercury looming on the horizon, EPA has issued an information collection request (ICR) for all coal- and oil-fired utility units of >25 MWe. The ICR is entitled "Information Collection Request for National Emission Standards for Hazardous Air Pollutants (NESHAP) for Coal- and Oil-Fired Electric Utility Steam-Generating Units." The data collected under this ICR will have a major impact on not just mercury standards but many other constituents on the hazardous air pollutants (HAPs) list that can be affected by mercury control technologies. An excerpt below from the ICR defines a utility unit as (1):

> "[A]ny fossil fuel-fired combustion unit of more than 25 megawatts that serves a generator that produces electricity for sale. A unit that cogenerates steam and electricity and supplies more than one-third of its potential electric output capacity and more than 25 MWe output to any utility power distribution system for sale is also considered a utility unit."

The ICR is divided into three parts, with subsets of units required to report under each part. The definitions for each part as well as the number of units required to report are as follows.

All facilities shall report:

- Part I – General Facility Information: Once for each facility. General facility information includes information such as name, address, size, pollution control devices, operator, fuel source, and emission data for which a permit is issued. All facilities shall have 90 days from receipt of notice to comply.

  All facilities meeting Section 112(a)(8) definition shall report:

- Part II – Fuel Analyses and Emission Data: Any fuel analysis performed in the preceding 12 calendar months and information about the fuel source. Emission data gathered during the same time frame are also requested. All facilities identified under Part II shall have 90 days from receipt of notice to comply.

All facilities identified to perform stack testing shall report:

- Part III – Emission Test Data: Units identified for sampling under Part III will be required to sample for one or more of the following HAP categories for coal-fired units:
  - Acid gas HAPs (e.g., HCl and HF)
  - Dioxin/furan organic HAPs
  - Non-dioxin/furan organic HAPs
  - Mercury and other nonmercury metallic HAPs
  - Other

Additional categories have been created for IGCC plants, oil-fired units, and petcoke-fired units. The categories for coal-fired units are described in more detail as follows.

Acid Gas HAPs

EPA has identified 175 units for the following sampling: HCl, HF, HCN, SO_2, O_2, CO_2, and moisture from the stack gases. The following will be determined from the coal fired during the test: chlorine, fluorine, and sulfur content; higher heating value (HHV); and proximate/ultimate analyses.

Dioxin/Furan Organic HAPs

EPA has identified 50 units to sample for dioxins/furans, including dioxins/furans, O_2, CO_2, and moisture from the stack gases. The following will be determined from the coal fired during the test: chlorine and sulfur content, HHV, and proximate/ultimate analyses.

Non-Dioxin/Furan Organic HAPs

EPA has identified 170 units to test for CO, volatile organic contaminants (VOC), and total hydrocarbon (THC). A subset of 50 units will be required to test for polycyclic organic matter (POM), NO_x, formaldehyde, methane, O_2, and CO_2, in addition to CO, VOC, and THC. All tested units will be required to test for moisture from the stack gases. The following will be determined from the coal fired during the test: HHV and proximate/ultimate analyses.

Mercury and Other Nonmercury Metallic HAPs

EPA has identified 170 units to test for Sb, As, Be, Cd, Cr, Co, Pb, Mn, Hg, Ni, Se, particulate matter (PM) (total filterable, fine [dry], fine [wet]), O_2, CO_2, and moisture. The following will be required from the coal fired during the test: the metals above (including Hg), chlorine, HHV, and proximate/ultimate analyses.

Other

EPA has selected 50 units to test for HCl, HF, HCN, SO_2, O_2, CO_2, CO, VOC, THC, POM, NO_x, formaldehyde, methane, Sb, As, Be, Cd, Cr, Co, Pb, Mn, Hg, Ni, Se, PM (total filterable, fine [dry], fine [wet]), and moisture from the stack gases. The following will be determined from the coal fired during the test: the metals above (including Hg); chlorine, fluorine, and sulfur content; HHV; and proximate/ultimate analyses.

Most of the sampling for the ICR was conducted during the summer of 2010. The data are due to EPA by the fall of 2010. A draft of the MACT rule is due March 2011, with a final rule due November 2011. Much attention in this ICR is being given to the level of HAPs without mercury control. Some of the units identified by EPA do have activated carbon injection (ACI) capability. However, this still may not adequately represent what impact mercury control would have on the level of HAPs in all cases. The cobenefits and impacts that mercury control will have on the complete power-generating system will become more important as MACT standards for all HAPs move forward.

Status of HAPs Work

Significant efforts are under way to develop promising control technologies to reduce Hg emissions from coal-fired power plants. Some of these technologies include ACI and the use of oxidizing agents and/or sorbent enhancement additives (SEAs) that help promote Hg oxidation and/or capture. Since elemental mercury (Hg^0) can be difficult to capture with existing control devices, oxidizing agents and SEAs have proven extremely beneficial for power plants firing coals that produce predominately elemental mercury in the flue gas stream. The use of these technologies for promoting Hg oxidation and improving Hg capture has the potential to impact the behavior of other HAPs in the flue gas stream. Extensive studies have been conducted to understand trace element emissions, partitioning, and speciation in flue gas (2–7). However, the addition of mercury technologies could impact inorganic HAPs, PM, or organic HAPs. The inorganic HAPs listed in the Clean Air Act Amendment of 1990 include antimony (Sb), arsenic (As), beryllium (Be), cadmium (Cd), chromium (Cr), cobalt (Co), lead (Pb), manganese (Mn), mercury (Hg), nickel (Ni), and selenium (Se). Although inorganic HAP data exist for pilot-scale and full-scale coal combustion test programs (8), very little information is available from test programs involving Hg control technologies. The organic and particulate HAPs include dioxins/furans, POM, VOCs, formaldehyde, methane, and PM.

To help evaluate the impact of new Hg control technologies on the fate of other HAPs, some additional efforts have been and are being included in existing and future test programs. An example of some of the emission and partitioning data (while applying Hg control technologies) for Cr, Pb, Ni, and Se that was gathered at recent EERC test sites can be found in Figures 1–4. Table 1 includes information on each of the test sites that provided data for the study (9).

For all six projects, metal HAP measurements were taken at the pollution control device outlet locations. The partitioning and emission results varied greatly. In general, for the majority of the HAPs measured, the removal was high with no large change between baseline and Hg control test conditions. The partitioning was not consistent among the different facilities, and there appeared to be a slight increase in total emissions for Cr, Ni, and Pb when Hg control technologies were applied. The consistency of the increase seems to indicate that there is a measurable amount of these elements being added as part of the Hg control technologies. Except for FS-3 (spray dryer absorber–fabric filter [SDA–FF]), Cr and Pb show a slight increase in gas-

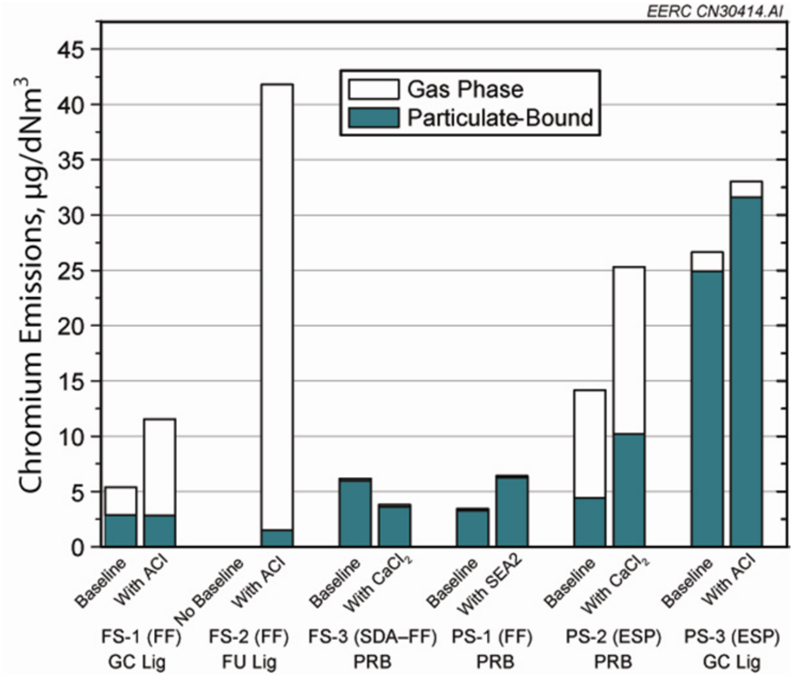


Figure 1. Chromium emissions and partitioning.

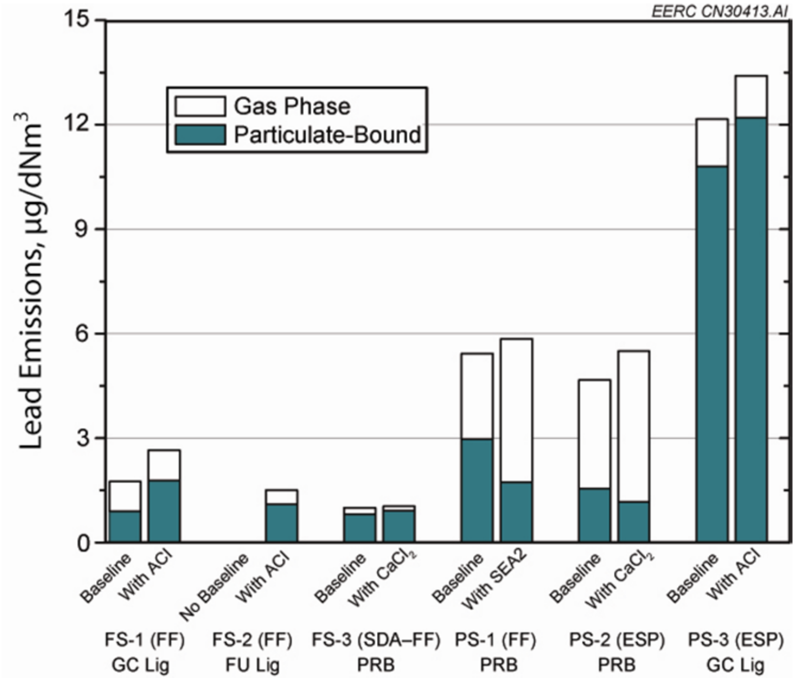


Figure 2. Lead emissions and partitioning.

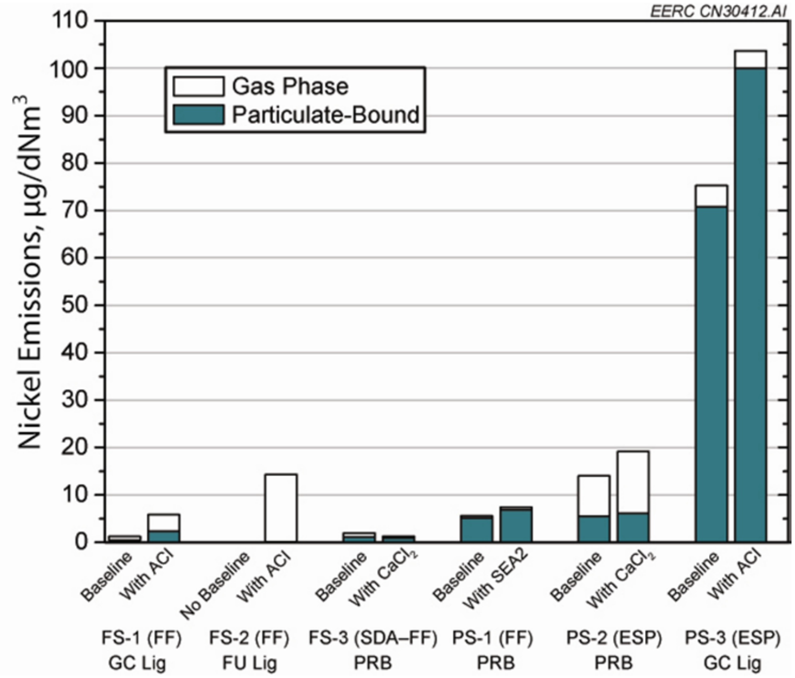


Figure 3. Nickel emissions and partitioning.

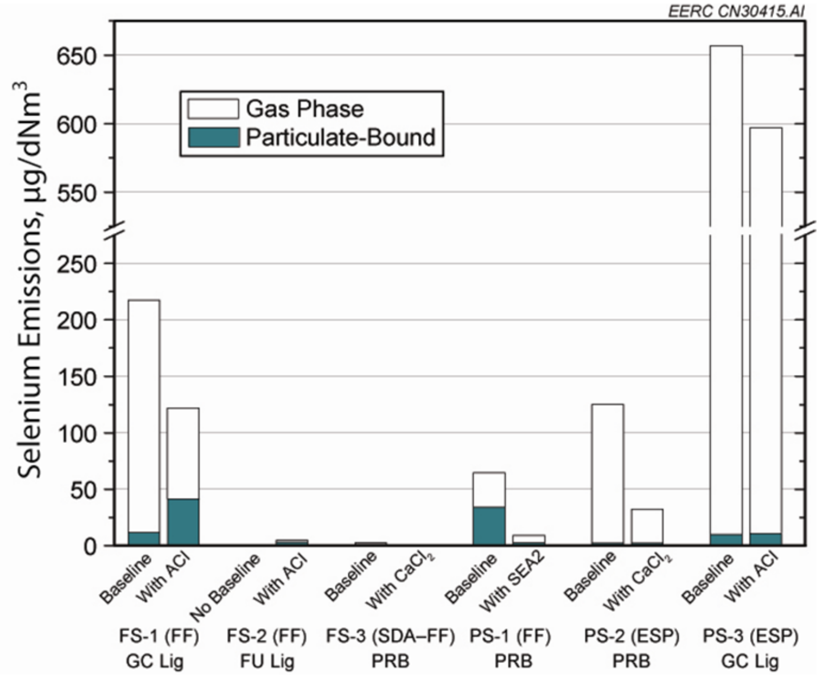


Figure 4. Selenium emissions and partitioning.

Table 1. Hg Control Projects Providing HAP Data

Project ID	Boiler	Coal Type Burned	Particulate Control	Hg Control Technology
FS-1	Full-scale (600 MW), pc[a]-fired	Gulf Coast lignite–PRB[c] blend	ESP–FF[b]	Enhanced ACI
FS-2	Full-scale (600 MW[d]), pc-fired	Fort Union (FU) lignite	ESP–FF	ACI
FS-3	Full-scale (550 MW), pc-fired	PRB subbituminous	SDA–FF	$CaCl_2$
PS-1	Pilot-scale (3,000,000 Btu/hr), CFBC[e]	PRB subbituminous	FF	SEA2
PS-2	Pilot-scale (500,000 Btu/hr), pc-fired	PRB subbituminous	ESP	$CaCl_2$
PS-3	Pilot-scale (500,000 Btu/hr), pc-fired	Gulf Coast lignite	ESP	ACI

[a] Pulverized coal.
[b] Electrostatic precipitator–fabric filter.
[c] Powder River Basin.
[d] A slipstream of ~2 MW was sampled from this unit.
[e] Circulating fluidized-bed combustor.

phase partitioning during Hg control. In all cases except for FS-3, Se partitioning was shifted toward the particulate phase and total emissions were reduced when Hg control technologies were applied. Similar results were seen by other researchers at a full-scale unit burning bituminous coal and injecting activated carbon at 10 and 20 lb/Macf, which resulted in significant enrichment of Se in the electrostatic precipitator (ESP) ash (10). The increase of some metal HAPs noted in this study will provide a basis for the additional sampling of metal HAPs. It will also become important to monitor any change in PM or organics while injecting powdered activated carbon (PAC) for mercury control; very little of this work has been done.

Sorbents and Additives

Through research conducted at the EERC and through the Center for Air Toxic Metals® (CATM®) research program, several SEAs have been developed and tested for their effectiveness in enhancing mercury removal. The intellectual property for these technologies is held within the EERC Foundation, which works with commercial partners to bring these technologies to the marketplace. In the case of SEAs, the EERC is working with Grünergy Technologies to commercialize EERC Foundation technologies. Grünergy Technologies is a U.S. energy technology firm, established in the field of emission-related product development, research, and commercialization. Grünergy Technologies has created and offers several proprietary solutions to improve plant operations and mitigate mercury emissions through the use of SEAs, carbon-based, and non-carbon-based sorbents. Additionally, Grünergy Technologies has a unique “concrete-friendly” technology that can preserve fly ash applications while being effective at controlling mercury emissions.

ICR Testing at Hoot Lake Plant

Otter Tail Power received an ICR letter from the EPA in December 2009, requesting its participation. As given by Attachment 13 of Supporting Statement B of the ICR, Hoot Lake Plant Unit 2 was one of 50 randomly selected units to test for all HAP groups except dioxin/furan. According to Supporting Statement B, the data from these 50 random units will be used to assess the impact of possible future HAP standards.

As given by Attachment 9 of Supporting Statement B of the ICR, Hoot Lake Plant Unit 3 was one of 50 randomly selected units to test for dioxin/furan. However, EPA indicated that it would consider allowing utilities to conduct this testing at substitute units as long as the substitute units were of similar size and type. Since Units 2 and 3 are substantially similar, Otter Tail requested to conduct the dioxin/furan testing at Unit 2. EPA approved this request in an e-mail dated January 14, 2010, from Bill Maxwell of EPA to Terry Graumann of Otter Tail Power Company.

GOALS AND OBJECTIVES

The primary goal was to perform the ICR sampling to meet the requirements of EPA and then repeat some of the sampling during the injection of a mercury reduction technology. These data will contribute to an immature database of generated information on the influence of sorbents on a unit’s stack emission. The following objectives were achieved through testing:

- Performed gas sampling and presented Otter Tail Power with the emission data for acid gas HAPs, mercury and nonmercury metallic HAPs, dioxin/furan HAPs, and nondioxin/furan organic HAPs to assist in the fulfillment of its ICR responsibilities.

- Provided mercury reduction information on a selected Grünergy Technologies SEA/sorbent combination for Hoot Lake Unit 2.

- Provided data on the emissions change of selected HAPs when a sorbent technology was injected.

- Calculated ESP mercury removal efficiencies from coal mercury concentrations and continuous mercury monitor (CMM) measurements at the ESP outlet.

DESCRIPTION OF TEST MATERIAL

One SEA and one sorbent provided by Grünergy Technologies were delivered on-site. These materials were selected by Grünergy Technologies as being the best suited to meet the requirements of Hoot Lake Unit 2 for mercury reduction. The materials are listed in Table 2.

Table 2. Sorbent/Additive Used During Testing

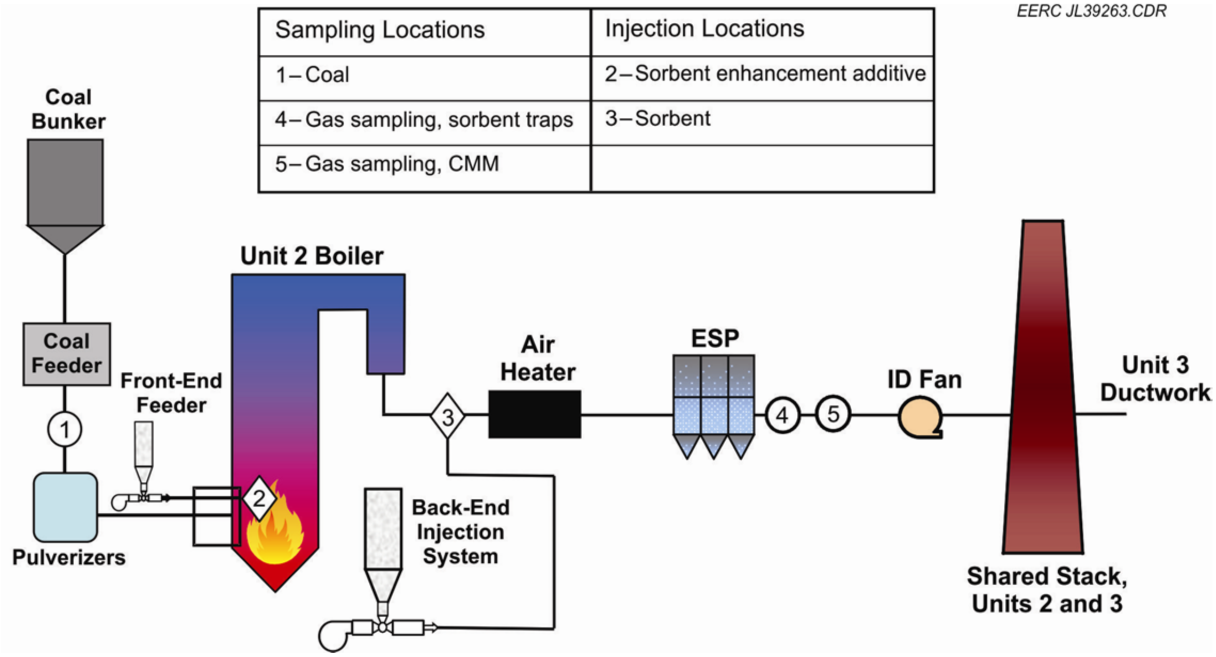
Material	Product Base Type
SF10	Noncarbon SEA
SB24	Carbon-based sorbent

DESCRIPTION OF TEST UNIT, SAMPLING LOCATIONS, AND EQUIPMENT

The test unit is a 54-MW unit with a tangentially-fired boiler fueled by Spring Creek subbituminous coal. Particulate matter is controlled by a cold-side ESP. A schematic that shows sampling and injection locations is presented in Figure 5.

Gas-Sampling Locations

The sampling location for the required ICR was located downstream of the ESP and composed of a vertical row of six ports. A picture of the location is shown in Figure 6. The port location is situated tightly between a shed and an access ladder to the top of the duct. For testing purposes, the ladder was removed and scaffolding erected to allow safe access to all ports for sampling personnel. These ports have been verified by Otter Tail Power to meet EPA Method 1 of Appendix A of Part 60 criteria based on a prior alternative test site evaluation conducted in accordance with EPA Method 1 Section 2.5 of Appendix A of Part 60. A single port, located halfway up the duct height and approximately 5 feet downstream of the vertical ports, served as the location for the hydrocarbon sampling and the mercury continuous emission monitor (CEM).



Sampling Locations	Injection Locations
1–Coal	2–Sorbent enhancement additive
4–Gas sampling, sorbent traps	3–Sorbent
5–Gas sampling, CMM	

Figure 5. Schematic of the test unit showing injection and sampling locations (ID stands for induced draft).

Figure 6. Port locations for sampling. Rightmost port was location for mercury CEM.

SEA Injection Location

The injection of sorbent was accomplished with a small feeder placed on the fourth-floor elevation of the boiler. All injection occurred at the northwest corner of the boiler. The material was injected via a lance inserted through a modified furnace door, as shown in Figure 7. The injection lance had an outer diameter of 1 inch and was 2 feet long. The feeder was calibrated on-site before the injection tests began.

Upstream of Air Heater Injection Location

Injection of sorbent was accomplished by the use of six ports located across the duct upstream of the air heater (AH). One-inch-diameter stainless steel lances were staggered in depth across the duct at alternating depths of 1.5 and 3.5 feet. The lance design is a simple 45° cut at the tip. The end of the lance was orientated so that the outlet of the lance faced downstream. Figure 8 shows the lances installed in the duct.

Injection Equipment

Furnace injection was carried out with a small K-Tron feeder system consisting of a screw feeder with a 30-lb-capacity hopper. Material is carried to the injection lance by use of an eductor connected to an air supply. After installation, a calibration curve was generated for the system. To operate, the system is powered and simply given a set point based on the calibration curve. During operation, the hopper was refilled as needed with material manually from 100-lb totes. The hopper was never allowed to be less than two-thirds full during the testing.

Figure 7. Modified furnace door showing injection lance installed at the northwestern corner of the boiler, fourth-floor level.

Figure 8. Sorbent injection lances located upstream of the AH. The distribution manifold can be seen connected to the main delivery line (black hose).

Sorbent injection was performed with a Norit Americas' PORTA-PAC® system that delivers material from suspended 900-lb sacks into a screw feeder to injection lances via an eductor. Before injection began, a calibration curve was generated. Set points were determined from the curve for selected feed rates. The system was checked every 30 minutes.

Sampling Methods

Test methods, traverse points, and analytical methods are given in Table 3. These methods were conducted following guidelines set forth in Title 40 of the Code of Federal Regulations Part 60 Appendix A (40 CFR Part 60) and listed on EPA's Technology Transfer Network Emissions Measurement Center Web site (www.epa.gov/tnn/emc) and EPA's online resource for SW-846 (Test Methods for Evaluating Solid Waste, Physical/Chemical Methods: www.epa.gov/osw/hazard/testmethods/sw846/online/index.htm).

Table 3. Test Matrix for ICR Sampling at Hoot Lake Power Plant Unit 2

Sampling Location	Analyte	No. Runs	Min. Time, hr	No. Traverse Points	EPA Sampling Method	Analytical Method
Unit 2 Duct	O_2 and CO_2	3	2	30 (6 × 5)	3B	Orsat
Unit 2 Duct	H_2O	3	2	30 (6 × 5)	4	Gravimetric
Unit 2 Duct	SO_2	3	2	Single pt.	6C or CEM	CEM
Unit 2 Duct	NO_x	3	2	Single pt.	7E or CEM	CEM
Unit 2 Duct	CO	3	2	Three pts. on centroidal area (1%)	10	CEM
Unit 2 Duct	THC	3	2	Single pt. on centroidal area (10%)	25A	GC–FID[1]
Unit 2 Duct	Speciated SVOCs[2]	3	2	30 (6 × 5)	0010	GC–MS[3]
Unit 2 Duct	Speciated VOCs	3 sets	4–20 min/sets	Single pt. on centroidal area (10%)	0031	GC–MS
Unit 2 Duct	Formaldehyde	3	2	30 (6 × 5)	0011	GC–MS
Unit 2 Duct	CH_4	3	2	Single pt. on centroidal area (1 m from wall)	18	GC/FID
Unit 2 Duct	Dioxins/furans	3	8	Long-line traverse	23	GC–MS
Unit 2 Duct	Halogens (HCl and HF)	3	1	30 (6 × 5)	26A	IC[4]
Unit 2 Duct	HCN	3	1	30 (6 × 5)	26A and OTM[5]-033	IC
Unit 2 Duct	$PM_{2.5}$	3	3.4 m^3 gas	12 (6 × 2)	OTM 27	Gravimetric
Unit 2 Duct	Condensable PM	3	4	12 (6 × 2)	OTM 28	Gravimetric/ Extraction
Unit 2 Duct	Metal HAPs (including Hg)	3	4	30 (6 × 5)	29	ICP–MS[6]

[1] Gas chromatography–flame ionization detection.
[2] Semivolatile organic compound.
[3] Gas chromatography–mass spectroscopy.
[4] Ion chromatography.
[5] Other Test Method.
[6] Inductively coupled plasma–mass spectrometry.

Two modifications were made to the EPA Method 29 procedure. As instructed by EPA on the ICR Web site (https://utilitymacticr.rti.org/FAQ/FAQEmissionsTesting.aspx#TEST-021), the procedure for preparation of mercury standards and sample analysis in Sections 13.4.1.1 through 13.4.1.3 of ASTM International (ASTM) D6784-02 (Standard Test Method for Elemental, Oxidized, Particle-Bound, and Total Mercury in Flue Gas Generated From Coal-Fired Stationary Sources [Ontario Hydro Method]) will be followed instead of the procedures in Sections 7.5.33 and 11.1.3 of EPA Method 29, and the quality assurance/quality control procedures in Section 13.4.2 of ASTM D6784-02 will be performed instead of the procedures in Section 9.2.3 of EPA Method 29.

OTM 27 and 28 were not run as separate tests but rather run in tandem. Requirements for each of these methods did not interfere with the other, so the decision was made to sample these two methods together in the interest of expediency.

EPA Test Method 1 (Sample and Velocity Traverses for Stationary Sources) was performed utilizing 30 traverse points in the 6 × 5 configuration to check cyclonic flow and the applicability of ports under Section 11.5 of the method. Acceptability criteria state that the average resultant angle must be less than or equal to 20 degrees, with a standard deviation of less than or equal to 10 degrees for the sample ports used. Method results revealed a resultant angle of 4.43 degrees, with a standard deviation of 3.81 degrees.

TEST COAL

Coal samples were taken by Otter Tail Power personnel throughout the program. During the ICR sampling portion of the program, coal samples were taken in during each of the EPA sampling method runs. These samples, which were not part of this test program, were analyzed by a laboratory selected by Otter Tail Power and the results entered directly into the EPA Electronic Reporting Tool (ERT).

During the sorbent/additive injection portion of the program, Otter Tail Power personnel took two coal samples a day for 6 days, following a modified ASTM D 2234 (Standard Practice for Collection of a Gross Sample of Coal) sampling method. These samples were brought back to the EERC for analysis of proximate/ultimate and Hg content.

Proximate and ultimate analyses were conducted on coal samples using ASTM Methods D3172 (Standard Practice for Proximate Analysis of Coal and Coke), D5142 (Standard Test Methods for Proximate Analysis of the Analysis Sample of Coal and Coke by Instrumental Procedures), and D3176 (Standard Practice for Ultimate Analysis of Coal and Coke). Coal mercury content was determined using cold-vapor atomic absorption spectroscopy according to EPA Method 245.1 (Determination of Mercury in Water by Cold-Vapor Atomic Absorption Spectrometry) and EPA SW-846 Method 7470 (Test Methods for Evaluating Solid Waste, Physical/Chemical Methods – Mercury in Liquid Waste [Manual Cold-Vapor Technique]).

TEST PLAN

The testing was divided into two separate test periods: ICR sampling and sorbent/additive injection. The decision to focus on the ICR sampling first was made to ensure that the sampling and analysis could be conducted and reported to EPA through the ERT process within the time constraints set forth by EPA. After a 2-week break, the EERC returned to perform injection testing and sampling. The test schedule is shown in Table 4. During a testing day, the unit was held at a steady, full load rate and maintained that rate until the day's activities were concluded. The unit went to full load at least 2 hours before any sampling began. Testing was not conducted overnight.

Grünergy's SEA (SF10) was injected into the burner in front of the furnace, and Grünergy-formulated sorbent SB24 was injected upstream of the AH. Parametric testing days were roughly 10 hours in length.

Parametric testing consisted of multiple injection rates (amounts) to establish a mercury removal curve. A mercury removal curve allows the data to be extrapolated beyond the last injection rate on the curve. This allows for approximate injection rates to be ascertained for any mercury removal rate of interest.

CEM and Sorbent Trap Sampling

The mercury CEM used was a Tekran Model 2537A, a gold amalgamation and cold-vapor atomic fluorescence spectroscopy (CVAFS)-based Hg vapor analyzer in conjunction with a PS Analytical S235C400 wet-chemistry conversion unit. CVAFS systems can only measure elemental mercury. The S235C400 uses two separate liquid flow paths, one to continuously reduce Hg^{2+} to Hg^0, resulting in a total gas-phase Hg sample, and the other to continuously scrub out Hg^{2+}, resulting in an Hg^0 sample. The S235C400 also uses a Peltier thermoelectric cooler module to cool and dry the sample gases prior to analysis. The Tekran instrument traps the Hg vapor from the conditioned sample onto a cartridge containing an ultrapure gold sorbent. The amalgamated Hg is then thermally desorbed and detected using atomic fluorescence

Table 4. Test Schedule

Dates, 2010	Description
ICR Sampling	
May 14–16	Arrive on-site and set up equipment
May 17–21	Sampling: EPA Methods 10, 23, 25A, OTM 27/28, and OTM-033
May 24–26	Sampling concludes: EPA Methods 26A, 29, and 0011
May 27	Secure equipment and leave plant
Sorbent/Additive Injection	
June 7–9	Install mercury CEM and set up injection equipment
June 10–11	Parametric testing of sorbent/additive
June 14–17	Constant rate of sorbent/additive injection with sampling: EPA Methods 26A, 29, and OTM 27/28
June 18	Pack up equipment and leave plant

spectrometry. A dual-cartridge design allows alternate sampling and desorption, resulting in continuous measurement of the sample stream. The Model 2537A allows two methods of calibration: manual injection or automatic permeation source. Permeation source calibration was used as the primary calibration to calibrate the instrument daily. Manual injection calibration on both cartridges was performed for verification. The Tekran instrument can measure either $Hg_{(T)}$ or Hg^0, with one analysis point being obtained approximately every 2.5 minutes. The system is designed only to measure the mercury concentration in the vapor phase, so the contribution of particulate-bound mercury was not measured.

A sorbent trap (ST) method (similar to EPA Method 30B) was used to evaluate the comparative accuracy of the CMM results. The ST samples were collected with single two-stage traps and analyzed with an OhioLumex mercury analyzer that is based on a thermal decomposition procedure validated by EPA, followed by detection using absorption spectroscopy. ST sampling was only used to initially validate the mercury CEM and was not used for the rest of the program.

RESULTS AND DISCUSSION

Average properties of the test coal are provided in Table 5 for each test period. Values are given on a dry basis for direct comparison. The standard deviation of the sorbent/additive injection coal samples is larger because of the smaller number of samples analyzed.

Sample size does not account for the standard variation seen in the mercury content. This coal does display a high variability and that is illustrated by Figure 9. This plot displays the mercury content of the 12 samples collected during the injection testing. High variability can be seen in the example of June 14 where the two coal values almost match the high and low range for the samples analyzed.

The average mercury content of the coal did rise between the two testing periods, but the overall heating value stayed the same. Ash content of coal appeared to be about 1% less during the sorbent injection testing.

ICR Sampling

ICR sampling was conducted from Monday, May 17, through Wednesday, May 26, 2010, with the exception of Saturday and Sunday (May 22 and 23). All methods required moisture, CO_2, and O_2 readings be taken during sampling. Table 6 lists the average values of each parameter taken from the sampling method runs. Tables 7–13 summarize the results of sampling. The values listed were calculated within the ERT giving results in the units listed. Additional data needed for the ERT calculations were entered by Otter Tail Power. In some cases, the measured value was below the accepted detection limits for the analytical method employed. Where applicable, those values are shaded.

The information was entered into the EPA ICR ERT and submitted August 2010.

Table 5. Average Properties of Test Coal, moisture-free basis

	ICR Sampling[a,b]		Sorbent/Additive Injection[c,d]	
Parameter	Average	Std. Dev.[e]	Average	Std. Dev.
Hg, ppm	0.0418	0.0108	0.0582	0.0090
Proximate Analysis, wt%				
Volatile Matter	41.60	0.30	34.20	0.38
Fixed Carbon	53.10	0.36	61.37	0.48
Ash	5.30	0.33	4.43	0.47
Ultimate Analysis, wt%				
Hydrogen	5.15	0.04	4.79	0.17
Carbon	73.95	0.36	76.07	0.99
Nitrogen	0.94	0.05	1.06	1.39
Sulfur	0.44	0.05	0.50	0.03
Oxygen	14.22	0.35	13.16	2.00
Heating Value, Btu/lb	12435	55	12371	80

[a] Based on 30 coal sample analyses.

[b] Average as-received moisture content is 26.08%.

[c] Based on 12 coal sample analyses.

[d] Average as-received moisture content is 26.28%.

[e] Standard deviation.

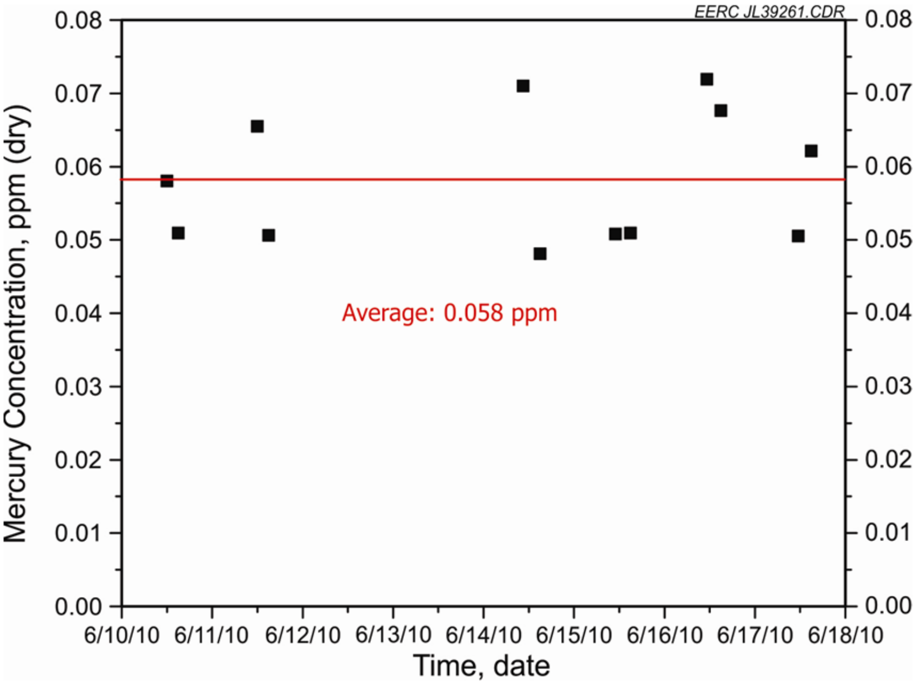


Figure 9. Comparison of day-to-day mercury concentration in the test coal.

Table 6. Average Value for Each Run for Oxygen (O_2), Carbon Dioxide (CO_2), and Moisture (H_2O)

Run No.: Units:	1 %	2 %	3 %
O_2	7.0	6.9	7.0
CO_2	11.7	11.8	11.9
H_2O	10.1	9.7	9.9

Table 7. Carbon Monoxide (CO), Total Organic Compounds (TOCs), Methane (CH_4), and Formaldehyde Results

Run No.:		1	
Units:	ppm	ppm at 7% O_2	lb/MMBtu
CO	3.62E-01	3.54E-01	3.80E-04
TOC as Propane	1.19E+00	1.18E+00	1.99E-03
Formaldehyde	1.08E-02	1.09E-02	1.25E-05
CH_4		7.01E-02	4.29E-05
Run No.:		2	
CO	3.67E-01	3.62E-01	3.88E-04
TOC as Propane	1.64E+00	1.63E+00	2.74E-03
Formaldehyde	5.16E-03	5.16E-03	5.94E-06
CH_4		6.89E-02	4.23E-05
Run No.:		3	
CO	7.51E-01	7.51E-01	8.07E-04
TOC as Propane	1.62E+00	1.61E+00	2.71E-03
Formaldehyde	2.05E-02	2.04E-02	2.35E-05
CH_4		2.44E-02	1.47E-05
Average Values			
CO	4.93E-01	4.89E-01	5.25E-04
TOC as Propane	1.48E+00	1.47E+00	2.48E-03
Formaldehyde	1.22E-02	1.22E-02	1.40E-05
CH_4		5.45E-02	3.33E-05

Table 8. Speciated Semivolatile Organic HAP Results*

Run No.:	1		2		3		Average	
Units:	ppm at 7% O_2	lb/MMBtu	ppm at 7% O_2	lb/MMBtu	ppm at 7% O_2	lb/MMBtu	ppm at 7% O_2	lb/MMBtu
1,2,4-Trichlorobenzene	3.42E-04	2.38E-06	3.77E-04	2.62E-06	3.42E-04	2.38E-06	3.54E-04	2.46E-06
1,2-Dichlorobenzene	4.23E-04	2.38E-06	4.66E-04	2.62E-06	4.23E-04	2.38E-06	4.37E-04	2.46E-06
1,3-Dichlorobenzene	4.23E-04	2.38E-06	4.66E-04	2.62E-06	4.23E-04	2.38E-06	4.37E-04	2.46E-06
1,4-Dichlorobenzene	4.23E-04	2.38E-06	4.66E-04	2.62E-06	4.23E-04	2.38E-06	4.37E-04	2.46E-06
1-Chloronaphthalene	3.82E-04	2.38E-06	4.21E-04	2.62E-06	3.82E-04	2.38E-06	3.95E-04	2.46E-06
1-Methylnaphthalene	8.90E-06	1.19E-07	2.94E-04	3.93E-06	8.90E-06	1.19E-07	1.04E-04	1.39E-06
1-Methylphenanthrene	1.07E-05	1.19E-07	1.18E-05	1.31E-07	1.07E-05	1.19E-07	1.10E-05	1.23E-07
2,4,5-Trichlorophenol	3.15E-04	2.38E-06	3.47E-04	2.62E-06	3.15E-04	2.38E-06	3.25E-04	2.46E-06
2,4,6-Trichlorophenol	2.62E-04	1.99E-06	2.89E-04	2.19E-06	2.62E-04	1.99E-06	2.71E-04	2.06E-06
2,4-Dichlorophenol	2.54E-04	1.59E-06	2.80E-04	1.75E-06	2.54E-04	1.59E-06	2.63E-04	1.64E-06
2,4-Dimethylphenol	5.09E-04	2.38E-06	5.60E-04	2.62E-06	5.09E-04	2.38E-06	5.26E-04	2.46E-06
2,4-Dinitrophenol	5.62E-04	3.97E-06	6.20E-04	4.38E-06	5.62E-04	3.97E-06	5.81E-04	4.11E-06
2,4-Dinitrotoluene	1.14E-04	7.94E-07	1.25E-04	8.75E-07	1.14E-04	7.94E-07	1.18E-04	8.21E-07
2,6-Dinitrotoluene	1.71E-04	1.91E-06	1.88E-04	1.31E-06	1.71E-04	1.91E-06	1.76E-04	1.71E-06
2-Chloronaphthalene	1.91E-05	1.91E-07	2.10E-04	1.31E-06	1.91E-05	1.91E-07	8.29E-05	5.64E-07
2-Chlorophenol	6.44E-04	3.18E-06	7.10E-04	3.50E-06	6.44E-04	3.18E-06	6.66E-04	3.29E-06
2-Methylanthracene	8.61E-06	1.91E-07	9.48E-06	1.31E-07	8.61E-06	1.91E-06	8.90E-06	7.44E-07
2-Methylnaphthalene	1.09E-05	5.96E-08	4.01E-04	2.19E-06	1.09E-05	5.96E-08	1.41E-04	7.70E-07
2-Methylphenol	8.62E-04	3.57E-06	9.50E-04	3.94E-06	8.62E-04	3.57E-06	8.91E-04	3.69E-06
2-Nitroaniline	1.50E-03	7.94E-06	1.65E-03	8.75E-06	1.50E-03	7.94E-06	1.55E-03	8.21E-06
2-Nitrophenol	3.72E-04	1.99E-06	4.10E-04	2.19E-06	3.72E-04	1.99E-06	3.85E-04	2.06E-06
3,3'-Dichlorobenzidine	3.27E-04	3.18E-06	3.61E-04	3.50E-06	3.27E-04	3.18E-06	3.38E-04	3.29E-06
3-Methylcholanthrene	2.31E-05	2.38E-07	2.55E-05	2.62E-07	2.31E-05	2.38E-07	2.39E-05	2.46E-07
3-Methylphenol	9.57E-04	3.97E-06	1.06E-03	4.38E-06	9.57E-04	3.97E-06	9.90E-04	4.11E-06
3-Nitroaniline	1.50E-03	7.94E-06	1.65E-03	8.75E-06	1.50E-03	7.94E-06	1.55E-03	8.21E-06
4,6-Dinitro-2-methylphenol	5.23E-04	3.97E-06	5.76E-04	4.38E-06	5.23E-04	3.97E-06	5.40E-04	4.11E-06
4-Bromophenyl Phenyl Ether	8.31E-05	7.94E-07	9.16E-05	8.75E-07	8.31E-05	7.94E-07	8.59E-05	8.21E-07
4-Chloro-3-methylphenol	3.63E-04	1.99E-06	4.00E-04	2.19E-06	3.63E-04	1.99E-06	3.75E-04	2.06E-06
4-Chloroaniline	1.62E-03	7.94E-06	1.79E-03	8.75E-06	1.62E-03	7.94E-06	1.68E-03	8.21E-06
4-Chlorophenyl Phenyl Ether	1.52E-04	1.91E-06	1.67E-04	1.31E-06	1.52E-04	1.91E-06	1.57E-04	1.71E-06

* Values in gray are below detection limits

Continued . . .

Table 8. Speciated Semivolatile Organic HAP Results* (continued)

Run No.:	1		2		3		Average	
Units:	ppm at 7% O_2	lb/MMBtu	ppm at 7% O_2	lb/MMBtu	ppm at 7% O_2	lb/MMBtu	ppm at 7% O_2	lb/MMBtu
4-Nitroaniline	1.50E-03	7.94E-06	1.65E-03	8.75E-06	1.50E-03	7.94E-06	1.55E-03	8.21E-06
4-Nitrophenol	7.44E-04	3.97E-06	8.20E-04	4.38E-06	7.44E-04	3.97E-06	7.70E-04	4.11E-06
7,12-Dimethylbenzo(a)-anthracene	2.42E-05	2.38E-07	2.67E-05	2.62E-07	2.42E-05	2.38E-07	2.51E-05	2.46E-07
9,10-Dimethylanthracene	2.14E-05	2.38E-07	2.35E-05	2.62E-07	2.14E-05	2.38E-07	2.21E-05	2.46E-07
Acenaphthene	1.01E-05	5.96E-08	1.48E-04	8.75E-06	1.01E-05	5.96E-08	5.60E-05	2.96E-06
Acenaphthylene	1.02E-05	5.63E-08	1.50E-04	8.27E-07	1.02E-05	5.63E-08	5.68E-05	3.13E-07
Aniline	2.22E-03	7.94E-06	2.45E-03	8.75E-06	2.22E-03	7.94E-06	2.30E-03	8.21E-06
Anthracene	8.71E-06	5.96E-08	6.40E-05	4.38E-07	8.71E-06	5.96E-08	2.71E-05	1.86E-07
Benz(a)anthracene	6.80E-06	5.96E-08	5.00E-05	4.38E-07	6.80E-06	5.96E-08	2.12E-05	1.86E-07
Benzidine	3.37E-03	2.38E-05	3.72E-03	2.62E-05	3.37E-03	2.38E-05	3.49E-03	2.46E-05
Benzo(a)fluorene	2.13E-05	2.38E-07	2.34E-05	2.62E-07	2.13E-05	2.38E-07	2.20E-05	2.46E-07
Benzo(a)pyrene	6.16E-06	5.96E-08	9.04E-05	8.75E-07	6.16E-06	5.96E-08	3.42E-05	3.31E-07
Benzo(b)fluoranthene	6.16E-06	5.96E-08	4.52E-05	4.38E-07	6.16E-06	5.96E-08	1.92E-05	1.86E-07
Benzo(b)fluorene	9.51E-06	1.19E-07	1.05E-05	1.31E-07	9.51E-06	1.19E-07	9.84E-06	1.23E-07
Benzo(e)pyrene	1.41E-05	1.19E-07	1.55E-05	1.31E-07	1.41E-05	1.19E-07	1.45E-05	1.23E-07
Benzo(g,h,i)perylene	3.75E-05	3.97E-07	4.13E-05	4.38E-07	3.75E-05	3.97E-07	3.87E-05	4.11E-07
Benzo(k)fluoranthene	6.16E-06	5.96E-08	9.04E-05	8.75E-07	6.16E-06	5.96E-08	3.42E-05	3.31E-07
Benzoic Acid	1.25E-02	5.84E-05	1.52E-02	7.13E-05	8.48E-04	5.84E-05	9.51E-03	6.27E-05
Benzyl Alcohol	5.74E-04	2.38E-06	6.33E-04	2.62E-06	5.74E-04	2.38E-06	5.94E-04	2.46E-06
Biphenyl	1.40E-05	1.19E-07	3.09E-04	2.62E-06	1.40E-05	1.19E-07	1.12E-04	9.53E-07
Bis(2-chloroethoxy)methane	2.39E-04	1.59E-06	2.64E-04	1.75E-06	2.39E-04	1.59E-06	2.47E-04	1.64E-06
Bis(2-chloroethyl) Eher	3.62E-04	1.99E-06	3.99E-04	2.19E-06	3.62E-04	1.99E-06	3.74E-04	2.06E-06
Bis(2-chloroisopropyl) Ether	3.03E-04	1.99E-06	3.33E-04	2.19E-06	3.03E-04	1.99E-06	3.13E-04	2.06E-06
Bis(2-ethylhexyl) Phthalate	2.12E-04	3.18E-06	2.34E-04	3.50E-06	2.12E-04	3.18E-06	2.19E-04	3.29E-06
Butyl Benzyl Phthalate	6.63E-05	7.94E-07	7.30E-05	8.75E-07	6.63E-05	7.94E-07	6.85E-05	8.21E-07
Carbazole	7.12E-04	7.94E-07	7.85E-04	8.75E-07	7.12E-04	7.94E-07	7.36E-04	8.21E-07
Chrysene	6.80E-06	5.96E-08	5.00E-05	4.38E-07	6.80E-06	5.96E-08	2.12E-05	1.86E-07
Coronene	3.24E-05	2.38E-07	3.57E-05	2.62E-07	3.24E-05	2.38E-07	3.35E-05	2.46E-07
Dibenz(a,h)anthracene	5.58E-06	5.96E-08	4.10E-05	4.38E-07	5.58E-06	5.96E-08	1.74E-05	1.86E-07

* Values in gray are below detection limits

Continued . . .

Table 8. Speciated Semivolatile Organic HAP Results* (continued)

Run No.:	1		2		3		Average	
Units:	ppm at 7% O_2	lb/MMBtu	ppm at 7% O_2	lb/MMBtu	ppm at 7% O_2	lb/MMBtu	ppm at 7% O_2	lb/MMBtu
Dibenzo(a,e)pyrene	2.05E-05	2.38E-07	2.26E-05	2.62E-07	2.05E-05	2.38E-07	2.12E-05	2.46E-07
Dibenzofuran	1.23E-03	7.94E-06	1.36E-03	8.75E-06	1.23E-03	7.94E-06	1.27E-03	8.21E-06
Diethyl Phthalate	1.40E-04	1.91E-06	1.54E-04	1.31E-06	1.40E-04	1.91E-06	1.45E-04	1.71E-06
Dimethyl Phthalate	1.60E-04	1.91E-06	1.76E-04	1.31E-06	1.60E-04	1.91E-06	1.65E-04	1.71E-06
Di-n-butyl Phthalate	1.12E-04	1.91E-06	1.23E-04	1.31E-06	1.12E-04	1.91E-06	1.15E-04	1.71E-06
Di-n-octyl Phthalate	7.95E-05	1.91E-06	8.76E-05	1.31E-06	7.95E-05	1.91E-06	8.22E-05	1.71E-06
Fluoranthene	7.68E-06	5.96E-08	5.64E-05	4.38E-07	5.12E-05	5.96E-08	3.84E-05	1.86E-07
Fluorene	9.34E-06	5.96E-08	6.86E-05	4.38E-07	9.34E-06	5.96E-08	2.91E-05	1.86E-07
Hexachlorobenzene	2.18E-04	2.38E-06	2.40E-04	2.62E-06	2.18E-04	2.38E-06	2.26E-04	2.46E-06
Hexachlorobutadiene	2.38E-04	2.38E-06	2.63E-04	2.62E-06	2.38E-04	2.38E-06	2.46E-04	2.46E-06
Hexachlorocyclopentadiene	2.28E-04	2.38E-06	2.51E-04	2.62E-06	2.28E-04	2.38E-06	2.35E-04	2.46E-06
Hexachloroethane	2.62E-04	2.38E-06	2.89E-04	2.62E-06	2.62E-04	2.38E-06	2.71E-04	2.46E-06
Indeno(1,2,3-cd)pyrene	5.62E-06	5.96E-08	8.26E-05	8.75E-07	5.62E-06	5.96E-08	3.13E-05	3.31E-07
Isophorone	7.49E-04	3.97E-06	8.25E-04	4.38E-06	7.49E-04	3.97E-06	7.75E-04	4.11E-06
m-Terphenyl	1.54E-05	1.91E-07	1.70E-05	1.31E-07	1.54E-05	1.91E-07	1.60E-05	1.71E-07
Naphthalene	2.83E-05	1.34E-07	1.78E-04	8.75E-07	2.42E-05	1.91E-07	7.68E-05	4.00E-07
Nitrobenzene	5.05E-04	2.38E-06	5.56E-04	2.62E-06	5.05E-04	2.38E-06	5.22E-04	2.46E-06
N-Nitrosodimethylamine	4.19E-03	1.91E-05	4.62E-03	1.31E-05	4.19E-03	1.91E-05	4.34E-03	1.71E-05
N-Nitrosodi-n-propylamine	4.77E-04	2.38E-06	5.26E-04	2.62E-06	4.77E-04	2.38E-06	4.93E-04	2.46E-06
N-Nitrosodiphenylamine	3.13E-04	2.38E-06	3.45E-04	2.62E-06	3.13E-04	2.38E-06	3.24E-04	2.46E-06
o-Terphenyl	1.07E-05	1.91E-07	1.18E-05	1.31E-07	1.07E-05	1.91E-07	1.10E-05	1.71E-07
Pentachlorophenol	3.50E-04	3.57E-06	3.86E-04	3.94E-06	3.50E-04	3.57E-06	3.62E-04	3.69E-06
Perylene	2.13E-05	2.38E-07	2.34E-05	2.62E-07	2.13E-05	2.38E-07	2.20E-05	2.46E-07
Phenanthrene	8.71E-06	5.96E-08	6.40E-05	4.38E-07	8.71E-06	5.96E-08	2.71E-05	1.86E-07
Phenol	5.50E-04	1.99E-06	6.06E-04	2.19E-06	5.50E-04	1.99E-06	5.69E-04	2.06E-06
p-Terphenyl	9.06E-06	1.91E-07	9.98E-06	1.31E-07	9.06E-06	1.91E-07	9.37E-06	1.71E-07
Pyrene	7.68E-06	5.96E-08	1.13E-04	8.75E-07	1.02E-04	5.96E-08	7.43E-05	3.31E-07
Quinoline	2.07E-05	2.38E-07	2.28E-05	2.62E-07	2.07E-05	2.38E-07	2.14E-05	2.46E-07
Tetralin	1.21E-05	1.91E-07	1.33E-05	1.31E-07	1.21E-05	1.91E-07	1.25E-05	1.71E-07

* Values in gray are below detection limits

Table 9. Speciated Volatile Organic HAP Results*

Run No.:	1		2		3		Average	
Units:	ppm at 7% O_2	lb/MMBtu	ppm at 7% O_2	lb/MMBtu	ppm at 7% O_2	lb/MMBtu	ppm at 7% O_2	lb/MMBtu
1,1,1,2-Tetrachloroethane	1.29E-03	8.32E-06	2.22E-03	1.43E-06	5.52E-03	3.55E-05	3.01E-03	1.51E-05
1,1,1-Trichloroethane	2.40E-03	1.23E-05	4.04E-03	2.07E-05	6.95E-03	3.55E-05	4.46E-03	2.28E-05
1,1,2,2-Tetrachloroethane	2.03E-03	1.31E-05	3.33E-03	2.15E-05	5.87E-03	3.78E-05	3.75E-03	2.41E-05
1,1,2-Trichloroethane	2.43E-03	1.24E-05	4.29E-03	2.20E-05	7.00E-03	3.58E-05	4.57E-03	2.34E-05
1,1-Dichloroethane	2.18E-03	8.27E-06	4.09E-03	1.55E-05	3.39E-03	1.29E-05	3.22E-03	1.22E-05
1,1-Dichloroethene	2.31E-03	8.59E-06	4.26E-03	1.58E-05	7.53E-03	2.80E-05	4.70E-03	1.75E-05
1,2,3-Trichloropropane	2.21E-03	1.25E-05	3.89E-03	2.20E-05	3.61E-03	2.04E-05	3.24E-03	1.83E-05
1,2-Dibromoethane	1.16E-03	8.32E-06	1.99E-03	1.43E-05	2.83E-03	2.04E-05	1.99E-03	1.43E-05
1,2-Dichlorobenzene	2.91E-03	1.64E-05	5.03E-03	2.84E-05	4.52E-03	2.55E-05	4.15E-03	2.34E-05
1,2-Dichloroethane	1.14E-03	4.32E-06	2.42E-03	9.19E-06	7.37E-03	2.80E-05	3.64E-03	1.38E-05
1,2-Dichloropropane	1.92E-03	8.32E-06	3.60E-03	1.56E-05	2.98E-03	1.29E-05	2.83E-03	1.23E-05
1,3-Dichlorobenzene	2.91E-03	1.64E-05	5.03E-03	2.84E-05	5.86E-03	3.30E-05	4.60E-03	2.59E-05
1,4-Dichlorobenzene	2.91E-03	1.64E-05	5.03E-03	2.84E-05	3.22E-03	1.81E-05	3.72E-03	2.10E-05
2-Butanone (MEK**)	1.21E-02	3.36E-05	2.08E-02	5.75E-05	1.29E-02	3.58E-05	1.53E-02	4.23E-05
2-Hexanone	6.98E-03	2.68E-05	1.33E-02	5.11E-05	5.38E-03	2.07E-05	8.55E-03	3.29E-05
4-Methyl-2-pentanone	4.88E-03	1.88E-05	7.98E-03	3.07E-05	6.61E-03	2.54E-05	6.49E-03	2.50E-05
Acetone	9.75E-02	2.20E-04	7.74E-02	1.73E-04	7.81E-02	1.74E-04	8.43E-02	1.89E-04
Benzene	2.79E-03	7.90E-06	4.78E-03	1.35E-05	5.97E-03	1.69E-05	4.51E-03	1.28E-05
Bromodichloromethane	1.32E-03	8.27E-06	2.47E-03	1.55E-05	3.24E-03	2.04E-05	2.34E-03	1.47E-05
Bromoform	1.26E-03	1.22E-05	2.13E-03	2.06E-05	2.62E-03	2.54E-05	2.00E-03	1.94E-05
Bromomethane	3.81E-03	1.39E-05	6.38E-03	2.32E-05	9.07E-03	3.30E-05	6.42E-03	2.34E-05
Carbon disulfide	7.01E-03	2.05E-05	1.10E-02	3.22E-05	1.30E-02	3.81E-05	1.04E-02	3.03E-05
Carbon tetrachloride	2.11E-03	1.24E-05	3.72E-03	2.20E-05	4.74E-03	2.80E-05	3.52E-03	2.08E-05
Chlorobenzene	1.93E-03	8.32E-06	3.61E-03	1.56E-05	4.73E-03	2.04E-05	3.42E-03	1.48E-05
Chlorodibromomethane	1.03E-03	8.26E-06	1.78E-03	1.43E-06	2.56E-03	2.04E-06	1.79E-03	3.91E-06
Chloroethane	3.47E-03	8.57E-06	5.89E-03	1.46E-05	7.34E-03	1.81E-05	5.56E-03	1.38E-05
Chloroform	1.81E-03	8.27E-06	3.39E-03	1.55E-05	4.45E-03	2.04E-05	3.22E-03	1.47E-05
Chloromethane	9.01E-03	1.16E-05	2.03E-02	3.93E-05	2.79E-02	5.39E-05	1.91E-02	3.49E-05
cis-1,2 Dichloroethene	2.31E-03	8.58E-06	3.92E-03	1.46E-05	6.85E-03	2.54E-05	4.36E-03	1.62E-05
cis-1,3-Dichloropropene	1.94E-03	8.27E-06	3.35E-03	1.46E-05	8.35E-03	3.55E-05	4.55E-03	1.95E-05
Dibromomethane	1.25E-03	8.32E-06	2.15E-03	1.43E-05	2.72E-03	1.81E-06	2.04E-03	8.14E-06
Dichlorodifluoromethane	3.59E-03	1.66E-05	6.17E-03	2.86E-05	4.39E-03	2.04E-05	4.72E-03	2.19E-05

* Values in gray are below detection limits. Method detection limits are calculated by using the standard deviation from a minimum of eight replicate low-level spikes.

** Methyl ethyl ketones.

Continued . . .

Table 9. Speciated Volatile Organic HAP Results* (continued)

Run No.:	1		2		3		Average	
Units:	ppm at 7% O_2	lb/MMBtu	ppm at 7% O_2	lb/MMBtu	ppm at 7% O_2	lb/MMBtu	ppm at 7% O_2	lb/MMBtu
Ethylbenzene	3.02E-03	1.23E-05	5.08E-03	2.04E-05	4.38E-03	1.78E-05	4.16E-03	1.68E-05
Iodomethane	2.29E-03	1.25E-05	4.04E-03	2.20E-05	3.28E-03	1.78E-05	3.20E-03	1.74E-05
Methylene Chloride	5.11E-03	1.66E-05	8.78E-03	2.86E-05	7.82E-03	2.55E-05	7.24E-03	2.36E-05
m-Xylene	3.05E-03	1.24E-05	5.40E-03	2.20E-05	4.40E-03	1.79E-05	4.28E-03	1.74E-05
o-Xylene	3.05E-03	1.24E-05	5.40E-03	2.20E-05	4.40E-03	1.79E-05	4.28E-03	1.74E-05
Styrene	2.08E-03	8.32E-06	3.90E-03	1.56E-05	7.02E-03	2.80E-05	4.33E-03	1.73E-05
Tetrachloroethene	2.58E-03	1.64E-05	4.26E-03	2.71E-05	4.12E-03	2.62E-05	3.65E-03	2.32E-05
Toluene	4.17E-03	9.80E-06	5.88E-03	2.08E-05	7.93E-03	2.80E-05	6.00E-03	1.95E-05
trans-1,2-Dichloroethene	2.31E-03	8.59E-06	3.92E-03	1.46E-05	4.81E-03	1.79E-05	3.68E-03	1.37E-05
trans-1,3-Dichloropropene	1.03E-03	4.37E-06	2.17E-03	9.24E-06	6.57E-03	2.80E-05	3.26E-03	1.39E-05
Trichloroethene	1.65E-03	8.32E-06	3.09E-03	1.56E-05	3.70E-03	1.87E-05	2.82E-03	1.42E-05
Trichlorofluoromethane	1.73E-03	6.06E-06	2.86E-03	1.51E-05	1.29E-02	6.80E-05	5.84E-03	2.97E-05
Vinyl Chloride	5.10E-03	1.22E-05	8.61E-03	2.06E-05	3.05E-02	7.31E-05	1.47E-02	3.53E-05

* Values in gray are below detection limits. Method detection limits are calculated by using the standard deviation from a minimum of eight replicate low-level spikes.

Table 10. Results for HCl, HF, and HCN*

Run No.:	1			
Units:	mg/dscm	mg/dscm at 7% O_2	lb/hr	lb/MMBtu
HF	3.21E-01	3.19E-01	1.87E-01	2.94E-04
HCl	7.55E-01	7.50E-01	4.40E-01	6.91E-04
HCN				2.56E-04
Run No.:	2			
HF	4.08E-01	4.05E-01	2.39E-01	3.73E-04
HCl	7.42E-01	7.37E-01	4.35E-01	6.79E-04
HCN				2.99E-04
Run No.:	3			
HF	4.71E-01	4.71E-01	2.71E-01	4.34E-04
HCl	7.54E-01	7.54E-01	4.34E-01	6.95E-04
HCN				2.99E-04
Average Values				
HF	4.00E-01	3.98E-01	2.32E-01	3.67E-04
HCl	7.50E-01	7.47E-01	4.36E-01	6.88E-04
HCN				2.85E-04

* Values in gray are below detection limits.

Table 11. Dixoin/Furan HAP Results*

Run No.:	1			2			3			Average		
Units:	ng/dscm	ng/dscm at 7% O_2	lb/MMBtu	ng/dscm	ng/dscm at 7% O_2	lb/MMBtu	ng/dscm	ng/dscm at 7% O_2	lb/MMBtu	ng/dscm	ng/dscm at 7% O_2	lb/MMBtu
1,2,3,4,6,7,8-HpCDD	4.51E-04	4.58E-04	4.22E-13	5.04E-04	5.08E-04	4.68E-13	4.89E-04	5.00E-04	4.60E-13	4.81E-04	4.89E-04	4.50E-13
1,2,3,4,6,7,8-HpCDF	2.20E-04	2.23E-04	2.06E-13	5.38E-04	5.42E-04	4.99E-13	5.12E-04	5.23E-04	4.82E-13	4.23E-04	4.29E-04	3.96E-13
1,2,3,4,7,8,9-HpCDF	2.00E-04	2.03E-04	1.87E-13	2.13E-04	2.15E-04	1.98E-13	2.50E-04	2.56E-04	2.36E-13	2.21E-04	2.25E-04	2.07E-13
1,2,3,4,7,8-HxCDD	1.60E-04	1.62E-04	1.50E-13	2.02E-04	2.03E-04	1.87E-13	1.82E-04	1.86E-04	1.71E-13	1.81E-04	1.84E-04	1.69E-13
1,2,3,4,7,8-HxCDF	1.60E-04	1.62E-04	1.50E-13	1.79E-04	1.80E-04	1.66E-13	1.93E-04	1.97E-04	1.82E-13	1.77E-04	1.80E-04	1.66E-13
1,2,3,6,7,8-HxCDD	1.70E-04	1.72E-04	1.59E-13	2.02E-04	2.03E-04	1.87E-13	1.82E-04	1.86E-04	1.71E-13	1.85E-04	1.87E-04	1.72E-13
1,2,3,6,7,8-HxCDF	1.40E-04	1.42E-04	1.31E-13	1.68E-04	1.69E-04	1.56E-13	1.82E-04	1.86E-04	1.71E-13	1.63E-04	1.66E-04	1.53E-13
1,2,3,7,8,9-HxCDD	1.60E-04	1.62E-04	1.50E-13	2.02E-04	2.03E-04	1.87E-13	1.82E-04	1.86E-04	1.71E-13	1.81E-04	1.84E-04	1.69E-13
1,2,3,7,8,9-HxCDF	1.80E-04	1.83E-04	1.69E-13	2.24E-04	2.26E-04	2.08E-13	2.39E-04	2.44E-04	2.25E-13	2.14E-04	2.18E-04	2.01E-13
1,2,3,7,8-PeCDD	1.60E-04	1.62E-04	1.50E-13	1.90E-04	1.91E-04	1.77E-13	2.05E-04	2.10E-04	1.93E-13	1.85E-04	1.88E-04	1.73E-13
1,2,3,7,8-PeCDF	2.40E-04	2.44E-04	2.25E-13	2.24E-04	2.26E-04	2.08E-13	1.93E-04	1.97E-04	1.82E-13	2.19E-04	2.22E-04	2.05E-13
2,3,3',4,4',5,5'-HpCB (PCB189)	8.32E-03	8.44E-03	7.78E-12	5.49E-03	5.53E-03	5.10E-12	2.27E-03	2.32E-03	2.14E-12	5.36E-03	5.43E-03	5.01E-12
2,3,3',4,4',5/2,3,3',4,4',5'-HxCB (PCBs156/157)	4.81E-03	4.88E-03	4.50E-12	5.94E-03	5.98E-03	5.51E-12	3.41E-03	3.49E-03	3.21E-12	4.72E-03	4.78E-03	4.41E-12
2,3,3',4,4'-PeCB (PCB105)	5.11E-03	5.18E-03	4.78E-12	8.74E-03	8.80E-03	8.11E-12	5.46E-03	5.58E-03	5.14E-12	6.44E-03	6.52E-03	6.01E-12
2,3',4,4',5,5'-HxCB (PCB167)	3.11E-03	3.16E-03	2.90E-12	2.35E-03	2.37E-03	2.18E-12	1.59E-03	1.63E-03	1.50E-12	2.35E-03	2.39E-03	2.19E-12
2,3,4,4',5-PeCB (PCB114)	1.50E-03	1.52E-03	1.41E-12	1.23E-03	1.24E-03	1.14E-12	1.13E-03	1.15E-03	1.06E-12	1.29E-03	1.30E-03	1.20E-12
2,3',4,4',5-PeCB (PCB118)	1.20E-03	1.22E-03	1.12E-12	2.02E-03	2.03E-03	1.87E-12	1.25E-03	1.28E-03	1.18E-12	1.49E-03	1.51E-03	1.39E-12
2',3,4,4',5-PeCB (PCB123)	1.60E-03	1.62E-03	1.50E-12	1.23E-03	1.24E-03	1.14E-12	1.14E-03	1.17E-03	1.07E-12	1.32E-03	1.34E-03	1.24E-12
2,3,4,6,7,8-HxCDF	2.00E-04	2.03E-04	1.87E-13	3.03E-04	3.05E-04	2.81E-13	2.16E-04	2.21E-04	2.03E-13	2.40E-04	2.43E-04	2.24E-13
2,3,4,7,8-PeCDF	3.01E-04	3.05E-04	2.81E-13	3.03E-04	3.05E-04	2.81E-13	2.50E-04	2.56E-04	2.36E-13	2.85E-04	2.89E-04	2.66E-13
2,3,7,8-TCDD	1.60E-04	1.62E-04	1.50E-13	2.02E-04	2.03E-04	1.87E-13	1.82E-04	1.86E-04	1.71E-13	1.81E-04	1.84E-04	1.69E-13
2,3,7,8-TCDF	1.42E-03	1.44E-03	1.33E-12	7.17E-04	7.22E-04	6.66E-13	5.80E-04	5.93E-04	5.46E-13	9.06E-04	9.18E-04	8.47E-13
3,3',4,4',5,5'-HxCB (PCB169)	3.11E-03	3.16E-03	2.90E-12	2.35E-03	2.37E-03	2.18E-12	1.59E-03	1.63E-03	1.50E-12	2.35E-03	2.39E-03	2.19E-12
3,3',4,4',5-PeCB (PCB126)	1.60E-03	1.62E-03	1.50E-12	1.23E-03	1.24E-03	1.14E-12	1.14E-03	1.17E-03	1.07E-12	1.32E-03	1.34E-03	1.24E-12

* Values in gray are below detection limits. Method detection limits are calculated by using the standard deviation from ten replicate low-level spikes.

Continued . . .

Table 11. Dixoin/Furan HAP Results* (continued)

Run No.:	1			2			3			Average		
Units:	ng/dscm	ng/dscm at 7% O_2	lb/MMBtu	ng/dscm	ng/dscm at 7% O_2	lb/MMBtu	ng/dscm	ng/dscm at 7% O_2	lb/MMBtu	ng/dscm	ng/dscm at 7% O_2	lb/MMBtu
3,3',4,4'-TCB (PCB77)	2.50E-03	2.54E-03	2.34E-12	2.35E-03	2.37E-03	2.18E-12	3.98E-03	4.07E-03	3.75E-12	2.94E-03	2.99E-03	2.76E-12
3,4,4',5-TCB (PCB81)	2.50E-03	2.54E-03	2.34E-12	2.35E-03	2.37E-03	2.18E-12	1.25E-03	1.28E-03	1.18E-12	2.03E-03	2.06E-03	1.90E-12
OCDD	2.33E-03	2.36E-03	2.18E-12	2.64E-03	2.66E-03	2.45E-12	2.68E-03	2.74E-03	2.53E-12	2.55E-03	2.59E-03	2.39E-12
OCDF	4.21E-04	4.27E-04	3.93E-13	6.72E-04	6.77E-04	6.24E-13	6.59E-04	6.74E-04	6.21E-13	5.84E-04	5.93E-04	5.46E-13
Other HpCDD	1.60E-04	1.62E-04	1.50E-13	1.79E-04	1.80E-04	1.66E-13	2.39E-04	2.44E-04	2.25E-13	1.93E-04	1.95E-04	1.80E-13
Other HpCDF	2.00E-04	2.03E-04	1.87E-13	2.24E-04	2.26E-04	2.08E-13	5.80E-04	5.93E-04	5.46E-13	3.35E-04	3.41E-04	3.14E-13
Other HxCDD	1.70E-04	1.72E-04	1.59E-13	1.90E-04	1.91E-04	1.77E-13	2.05E-04	2.10E-04	1.93E-13	1.88E-04	1.91E-04	1.76E-13
Other HxCDF	1.90E-04	1.93E-04	1.78E-13	2.13E-04	2.15E-04	1.98E-13	2.05E-04	2.10E-04	1.93E-13	2.03E-04	2.06E-04	1.90E-13
Other PeCDD	1.60E-04	1.62E-04	1.50E-13	1.79E-04	1.80E-04	1.66E-13	4.43E-04	4.53E-04	4.18E-13	2.61E-04	2.65E-04	2.45E-13
Other PeCDF	4.11E-04	4.17E-04	3.84E-13	2.24E-04	2.26E-04	2.08E-13	1.93E-04	1.97E-04	1.82E-13	2.76E-04	2.80E-04	2.58E-13
Other TCDD	1.60E-04	1.62E-04	1.50E-13	2.02E-04	2.03E-04	1.87E-13	1.82E-04	1.86E-04	1.71E-13	1.81E-04	1.84E-04	1.69E-13
Other TCDF	5.19E-03	5.27E-03	4.85E-12	6.83E-04	6.88E-04	6.34E-13	1.11E-03	1.13E-03	1.05E-12	2.33E-03	2.36E-03	2.18E-12
Total Dioxins	3.89E-03	3.95E-03	3.64E-12	4.24E-03	4.27E-03	3.93E-12	5.59E-03	5.71E-03	5.27E-12	4.57E-03	4.64E-03	4.28E-12
Total Furans	8.44E-03	8.56E-03	7.89E-12	3.31E-03	3.33E-03	3.07E-12	3.39E-03	3.46E-03	3.19E-12	5.05E-03	5.12E-03	4.72E-12

* Values in gray are below detection limits. Method detection limits are calculated by using the standard deviation from ten replicate low-level spikes.

Table 12. Particulate Matter Sampling Results

Run No.:	1	2	3	Average
Units:	lb/MMBtu			
Filterable				
Total Filterable Particulate	8.01E-02	9.23E-02	1.00E-01	9.08E-02
Filterable $PM_{2.5}$	2.06E-02	2.19E-02	2.01E-02	2.08E-02
Condensable				
Inorganic (aqueous) Condensable Particulate	1.65E-03	1.74E-03	1.57E-03	1.65E-03
Organic Condensable Particulate	2.47E-04	2.52E-04	2.79E-04	2.59E-04
Total Condensables	1.90E-03	1.99E-03	1.85E-03	1.91E-03
Total (Filterable + Condensable)				
Total Particulate	8.19E-02	9.43E-02	1.02E-01	9.27E-02
Total $PM_{2.5}$	2.25E-02	2.39E-02	2.18E-02	2.27E-02

Table 13. Mercury and Metallic HAP Sampling Results

Run No.:	1			
Units:	lb/hr	lb/MMBtu	mg/dscm	mg/dscm at 7% O_2
Antimony	2.98E-04	4.62E-07	5.04E-04	5.00E-04
Arsenic	2.60E-03	4.03E-06	4.41E-03	4.38E-03
Beryllium	1.51E-04	2.34E-07	2.56E-04	2.54E-04
Cadmium	7.84E-05	1.21E-07	1.33E-04	1.32E-04
Chromium	2.48E-03	3.84E-06	4.20E-03	4.17E-03
Cobalt	1.15E-03	1.78E-06	1.94E-03	1.93E-03
Filterable Particulate	3.66E+01	5.68E-02	6.20E+01	6.16E+01
Lead	2.27E-03	3.52E-06	3.85E-03	3.82E-03
Manganese	1.49E-02	2.31E-05	2.52E-02	2.50E-02
Mercury	3.70E-03	5.73E-06	6.27E-03	6.23E-03
Nickel	1.58E-03	2.44E-06	2.67E-03	2.65E-03
Selenium	2.32E-03	3.60E-06	3.93E-03	3.90E-03
Run No.:	2			
Antimony	6.45E-04	9.37E-07	1.08E-03	1.02E-03
Arsenic	3.54E-03	5.16E-06	5.92E-03	5.60E-03
Beryllium	1.78E-04	2.59E-07	2.97E-04	2.81E-04
Cadmium	6.12E-04	8.90E-07	1.02E-03	9.64E-04
Chromium	3.04E-03	4.43E-06	5.08E-03	4.80E-03
Cobalt	1.49E-03	2.17E-06	2.49E-03	2.35E-03
Filterable Particulate	5.04E+01	7.33E-02	8.41E+01	7.95E+01
Lead	2.92E-03	4.24E-06	4.87E-03	4.60E-03

Continued . . .

Table 13. Mercury and Metallic HAP Sampling Results (continued)

Run No.:	2			
Units:	lb/hr	lb/MMBtu	mg/dscm	mg/dscm at 7% O_2
Manganese	1.78E-02	2.59E-05	2.97E-02	2.81E-02
Mercury	3.56E-03	5.18E-06	5.94E-03	5.62E-03
Nickel	2.29E-03	3.33E-06	3.82E-03	3.61E-03
Selenium	2.29E-03	3.33E-06	3.82E-03	3.61E-03
Run No.:	3			
Antimony	6.95E-04	1.03E-06	1.17E-03	1.11E-03
Arsenic	4.52E-03	6.69E-06	7.63E-03	7.26E-03
Beryllium	1.61E-04	2.38E-07	2.71E-04	2.58E-04
Cadmium	1.13E-04	1.68E-07	1.91E-04	1.82E-04
Chromium	3.46E-03	5.11E-06	5.83E-03	5.55E-03
Cobalt	1.80E-03	2.66E-06	3.03E-03	2.88E-03
Filterable Particulate	5.64E+01	8.35E-02	9.52E+01	9.06E+01
Lead	3.12E-03	4.61E-06	5.26E-03	5.01E-03
Manganese	2.03E-02	3.01E-05	3.43E-02	3.27E-02
Mercury	4.61E-03	6.82E-06	7.77E-03	7.40E-03
Nickel	2.53E-03	3.74E-06	4.26E-03	4.06E-03
Selenium	2.34E-03	3.46E-06	3.94E-03	3.75E-03
Average Values				
Antimony	5.46E-04	8.10E-07	9.18E-04	8.77E-04
Arsenic	3.55E-03	5.29E-06	5.99E-03	5.75E-03
Beryllium	1.63E-04	2.44E-07	2.75E-04	2.64E-04
Cadmium	2.68E-04	3.93E-07	4.48E-04	4.26E-04
Chromium	2.99E-03	4.46E-06	5.04E-03	4.84E-03
Cobalt	1.48E-03	2.20E-06	2.49E-03	2.39E-03
Filterable Particulate	4.78E+01	7.12E-02	8.04E+01	7.72E+01
Lead	2.77E-03	4.12E-06	4.66E-03	4.48E-03
Manganese	1.77E-02	2.64E-05	2.97E-02	2.86E-02
Mercury	3.96E-03	5.91E-06	6.66E-03	6.42E-03
Nickel	2.13E-03	3.17E-06	3.58E-03	3.44E-03
Selenium	2.32E-03	3.46E-06	3.90E-03	3.75E-03

Sorbent/Additive Injection

Sampling personnel returned to Unit 2 and began injection testing in conjunction with a repeat of selected flue gas sampling from Monday, June 7, through Friday, June 18, 2010, with the exception of Saturday and Sunday (June 12 and 13). Two days of parametric testing with the Grünergy-provided sorbent and additive was conducted followed by 4 days of injection with a set injection rate. Table 14 lists the injection rates used during testing. For the selected combination of SB24/SB10, it was indicated by Grünergy that the optimum combination for

Table 14. Sorbent/Additive Injection Rates Used During Testing

	Additive SF10		Sorbent SB24	
	lb/hr	lb/Macf	lb/hr	lb/Macf
Rate 1	2	0.17	10	0.85
Rate 2	4	0.34	20	1.71
Rate 3	5	0.43	25	2.13
Rate 4	5.5	0.47	27.5	2.35
Rate 5	6	0.51	30	2.56
Rate 6	7	0.60	35	2.99
Rate 7	8	0.68	40	3.41
Rate 8	10	0.85	50	4.27

sorbent to additive is to maintain rates where the additive is injected at one-fifth the rate of the sorbent. This ratio was maintained during all injections. After an injection rate was found for approximately 80% mercury reduction, the injection rates were held constant during which flue gas sampling was conducted that included EPA Method 26a, Method 29, and OTM 27/28. All gas-sampling methods were conducted in triplicate.

The Hg removals measured during parametric testing are shown in Figure 10. A few of the parametric rates were repeated and the duplicates are also given. Three of these repeat tests are much lower than the original test. This is believed to be a change in mercury content of the coal and not from other variables. The repeat tests were conducted during the same time period, separate from the original run, and so this is the most likely cause. Also, the calculated Hg removal curve based on the mercury content in the coal is different from the curve generated based on relative difference from baseline of the ESP outlet mercury CEM. The baseline mercury CEM value was taken from the average values from baseline (nontesting) conditions on June 9 and 10 and the beginning of June 11. This lower removal value based on coal has been observed before at a few other plants, but an explanation has not yet been determined for this phenomenon. The average total mercury concentration at the exit of the ESP, as measured by mercury CEM was measured to be 6.54 µg/dNm^3 at 7% O_2 (8.40 µg/dNm^3 at 3% O_2) and the average elemental mercury concentration was measured to be 4.85 µg/dNm^3 at 7% O_2 (6.24 µg/dNm^3 at 3% O_2). Values were given on a 7% O_2 basis because the ERT calculated other values based on that oxygen level. The 3% O_2 values were also given for typical reporting convention.

Parametric testing indicated that 75% mercury removal can be achieved with a Grünergy sorbent/additive combination of 1.71/0.34 lb/Macf, respectively. Increasing the rate combination to 2.35/0.47 lb/Macf would produce mercury removals above 85%, and to achieve greater than 90% removal would require injection rates above 4.27/0.85 lb/Macf.

Parametric rates were measured over a period of a few hours and yield an estimate of performance for a given rate. Variation in plant conditions and fuel can change results over a longer period. Even so, the combination rate of 2.13/0.43 lb/Macf was selected to achieve the range of 80% to 85% removal during sampling.

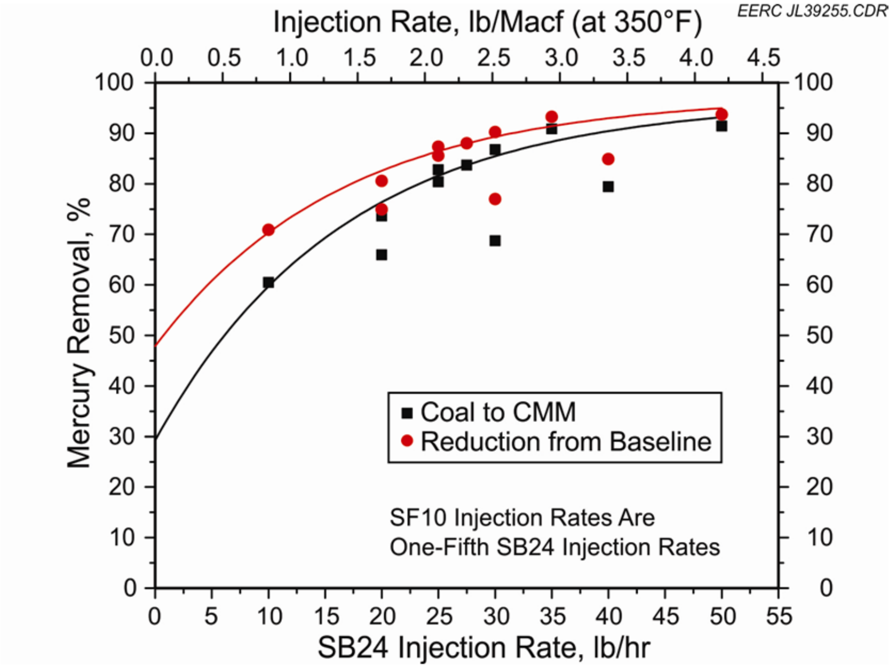


Figure 10. Stack percent mercury removals as a function of parametric SF10–SB24 injection rates. Injection rates are for the entire unit.

Figure 11 plots the mercury CEM data during fixed-rate injection over 4 days. During this time, the gas sampling was completed. Injection was started in the morning and held for 1 to 2 hours before sampling began. Mercury reduction did change over time and is most likely a result of changes in coal mercury concentration. Even though the concentration changed, the overall target of 80%–85% was achieved and even slightly surpassed.

The results of flue gas sampling are given in Tables 15–17. Plant data were not collected during this phase, and so the results are given in general units. This is especially important related to the particulate data. The ICR values as reported in the ERT were calculated on the basis of lb/MMBtu. To perform this unit conversion with the collected data would result in approximations that could not be compared directly with ICR data. For comparisons, the data are shown in Figures 12–14 alongside the results from the ICR sampling.

Comparing particulate matter results to the ICR sampling shows that the overall total filterable particulate and filterable $PM_{2.5}$ loadings dropped. The inorganic and organic condensables increased. Hydrogen chloride concentrations did not change, but hydrogen fluoride did increase significantly. Metallic HAP results did vary widely (as shown with rather large standard deviations), and so changes in concentration are difficult to determine. It does appear that beryllium, cobalt, and mercury were reduced with mercury having the largest reduction, as expected. Selenium concentration appeared to increase. Coal analysis results in Table 5 show that the ash content was less during the injection testing by almost 0.9%. Because of this, the direct effect of injection on particulate emission cannot be directly related without additional sampling.

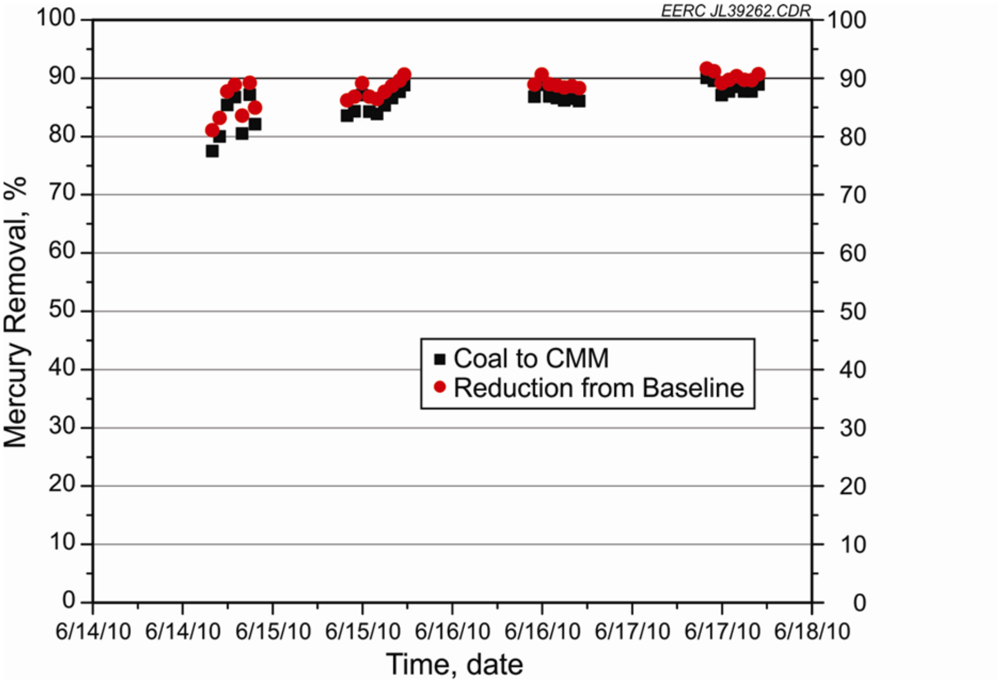


Figure 11. Hourly stack mercury removals during the SF10–SB24 extended test. SF10 and SB24 injection rates were 5 lb/hr (0.4 lb/Macf) and 25 lb/hr (2.1 lb/Macf), respectively.

Table 15. Particulate Matter Sampling Results During Sorbent/Additive Injection, grains/scf

Run No.:	1	2	3	Average
Filterable				
Total Filterable Particulate	3.15E-02	2.89E-02	3.05E-02	3.03E-02
Filterable $PM_{2.5}$	7.84E-03	6.84E-03	6.63E-03	7.10E-03
Condensable				
Inorganic (aqueous) Condensable Particulate	2.32E-03	1.97E-03	1.68E-03	1.99E-03
Organic Condensable Particulate	5.52E-.04	5.91E-04	5.43E-04	5.62E-04
Total Condensables	2.87E-03	2.56E-03	2.23E-03	2.55E-03
Total (Filterable + Condensable)				
Total Particulate	3.44E-02	3.14E-02	3.28E-02	3.29E-02
Total $PM_{2.5}$	1.07E-02	9.41E-03	8.86E-03	9.66E-02

Table 16. Results for HCl and HF During Sorbent/Additive Injection

Units:	mg/dscm	mg/dscm at 7% O_2	lb/hr
Run 1			
HF	9.33E-01	9.13E-01	5.54E-01
HCl	7.52E-01	7.36E-01	4.47E-01
Run 2			
HF	9.50E-01	9.50E-01	5.61E-01
HCl	7.60E-01	7.60E-01	4.49E-01
Run 3			
HF	9.01E-01	8.82E-01	5.25E-01
HCl	7.57E-01	7.41E-01	4.41E-01
Average Values			
HF	9.28E-01	9.15E-01	5.47E-01
HCl	7.56E-01	7.46E-01	4.46E-01

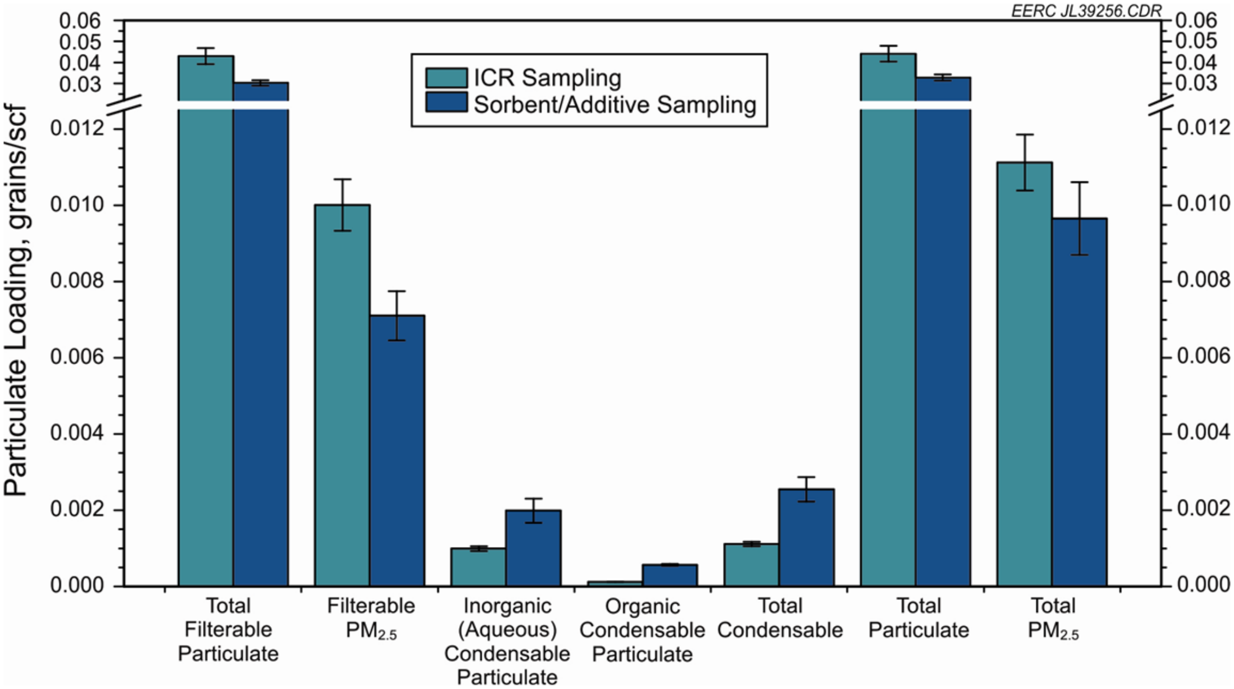


Figure 12. Comparison of particulate data from ICR sampling and sorbent/additive sampling. Error bars are the standard deviation of the three runs.

Table 17. Mercury and Metallic HAP Sampling Results During Sorbent/Additive Injection

Units:			
Run 1	mg/dscm	mg/dscm at 7% O_2	lb/hr
Antimony	1.05E-03	1.04E-03	6.10E-04
Arsenic	4.61E-03	4.54E-03	2.69E-03
Beryllium	1.89E-04	1.86E-04	1.10E-04
Cadmium	3.60E-04	3.55E-04	2.10E-04
Chromium	6.26E-03	6.17E-03	3.66E-03
Cobalt	1.54E-03	1.52E-03	9.02E-04
Filterable Particulate	7.81E+01	7.70E+01	4.56E+01
Lead	6.35E-03	6.26E-03	3.71E-03
Manganese	3.60E-02	3.55E-02	2.10E-02
Mercury	7.35E-04	7.25E-04	4.29E-04
Nickel	3.51E-03	3.46E-03	2.05E-03
Selenium	6.88E-03	6.78E-03	4.02E-03
Run 2			
Antimony	9.77E-04	9.63E-04	5.82E-04
Arsenic	3.82E-03	3.77E-03	2.27E-03
Beryllium	1.77E-04	1.74E-04	1.05E-04
Cadmium	2.82E-04	2.78E-04	1.68E-04
Chromium	3.36E-03	3.31E-03	2.00E-03
Cobalt	1.33E-03	1.31E-03	7.91E-04
Filterable Particulate	7.46E+01	7.35E+01	4.44E+01
Lead	2.96E-03	2.92E-03	1.76E-03
Manganese	3.19E-02	3.14E-02	1.90E-02
Mercury	6.72E-04	6.62E-04	4.00E-04
Nickel	2.89E-03	2.85E-03	1.72E-03
Selenium	5.67E-03	5.59E-03	3.38E-03
Run 3			
Antimony	9.00E-04	8.63E-04	5.14E-04
Arsenic	3.27E-03	3.13E-03	1.87E-03
Beryllium	1.46E-04	1.40E-04	8.35E-05
Cadmium	2.10E-04	2.01E-04	1.20E-04
Chromium	2.31E-03	2.21E-03	1.32E-03
Cobalt	9.73E-04	9.33E-04	5.56E-04
Filterable Particulate	4.65E+01	4.46E+01	2.66E+01
Lead	2.25E-03	2.16E-03	1.28E-03
Manganese	2.16E-02	2.07E-02	1.24E-02
Mercury	7.21E-04	6.91E-04	4.13E-04
Nickel	1.72E-03	1.65E-03	9.84E-04
Selenium	5.58E-03	5.35E-03	3.19E-03
Average Values			
Antimony	9.76E-04	9.55E-04	5.69E-04
Arsenic	3.90E-03	3.81E-03	2.28E-03
Beryllium	1.71E-04	1.67E-04	9.95E-05
Cadmium	2.84E-04	2.78E-04	1.66E-04
Chromium	3.98E-03	3.90E-03	2.33E-03
Cobalt	1.28E-03	1.25E-03	7.50E-04
Filterable Particulate	6.64E+01	6.50E+01	3.89E+01
Lead	3.85E-03	3.78E-03	2.25E-03
Manganese	2.98E-02	2.92E-02	1.75E-02
Mercury	7.09E-04	6.93E-04	4.14E-04
Nickel	2.71E-03	2.65E-03	1.58E-03
Selenium	6.04E-03	5.91E-03	3.53E-03

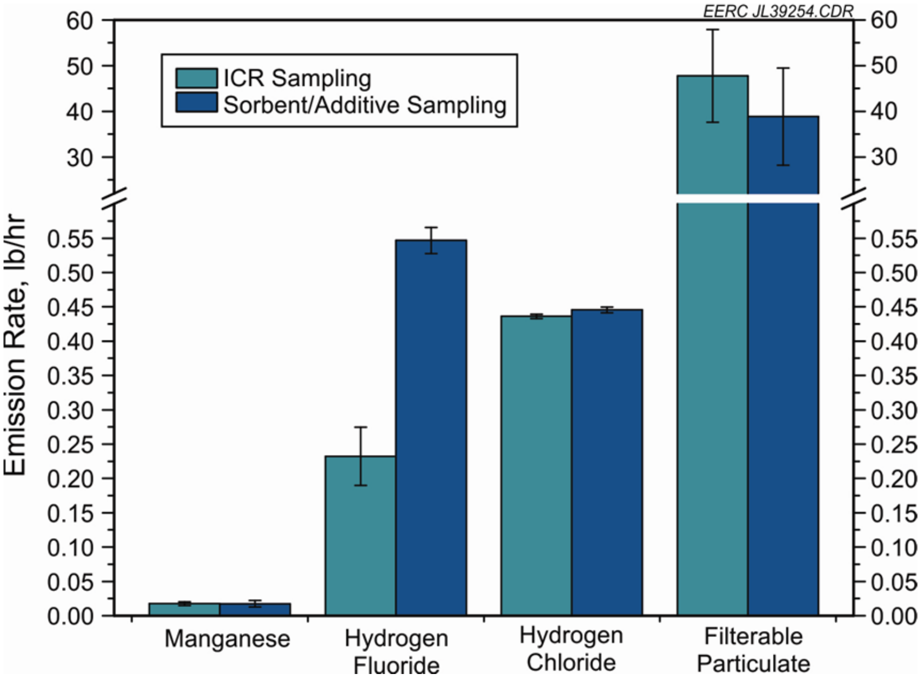


Figure 13. EPA Method 26 and selected EPA Method 29 results. Error bars are the standard deviation of the three runs.

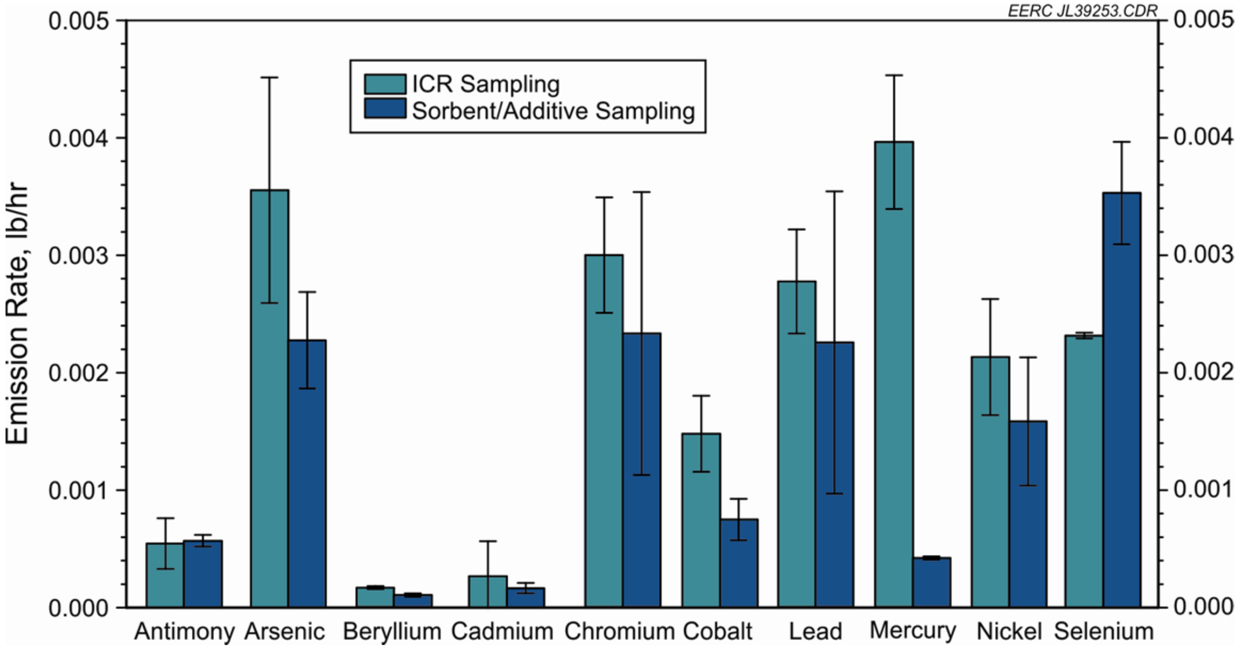


Figure 14. EPA Method 29 results comparison. Error bars are the standard deviation of the three runs.

CONCLUSIONS

The ICR requirements for the Hoot Lake Plant Unit 2 were successfully met. The data were compiled and entered into the EPA ERT and submitted to EPA August 2010. This site was especially challenging because of plant configuration and port placement but the challenges were overcome.

In addition, a mercury control technology provided by Grünergy Technologies was parametrically tested for its effectiveness. Results indicate that a mercury removal rate of 75% can be achieved across the ESP with the combination of a sorbent injection rate of 1.71 lb/Macf upstream of the AH and an additive injection rate of 0.34 lb/Macf into the boiler. It was determined that 85% reduction can be achieved with a combined injection of sorbent/additive of 2.35/0.47 lb/Macf, respectively. Greater than 90% removal can be attained but would require sorbent/additive injection rates above 4.27/0.85 lb/Macf, respectively.

Selected particulate, acid gas, and metallic HAPs were also sampled during a 4-day period, where the injection of sorbent/additive was maintained at a constant rate during the day but not at night. When comparing the results to values obtained during the ICR sampling, it was found that the overall total filterable particulate and filterable $PM_{2.5}$ loadings decreased, the inorganic and organic condensables increased, hydrogen chloride was unchanged, but hydrogen fluoride was significantly increased. The ash content of the coal did change between ICR and injection sampling, so direct effect of injection with particulate loading cannot be determined with just the three particulate tests conducted here. There have been anecdotal observations of particulate loading decrease across an ESP at a few other plants, but data have not been presented to the public to date. Metallic HAP concentrations varied widely but did seem to indicate that beryllium and cobalt did decrease. Selenium, however, appeared to increase. As expected, mercury concentrations decreased.

Partitioning of the particulate and gaseous-phase contributions of these sampling techniques were not evaluated in this project, but further work needs to be done to evaluate them. This project also developed results that were highly varied from one test run to another for each parameter. Further testing with a much more intense sampling strategy should be employed to better reduce uncertainty.

REFERENCES

1. U.S. Environmental Protection Agency. *Information Collection Effort for New and Existing Coal- and Oil-Fired Electric Utility Steam-Generating Units*; EPA ICR No. 2362.01 (OMB Control No. 2060-0631); Dec 2009; www.epa.gov (accessed Dec 2009).

2. Guo, X.; Zheng, C.G. Characterization of Arsenic Emissions from a Coal-Fired Power Plant. *Environ. Sci*. **2006**, *27*, 631–635.

3. Lopez-Anton, M.A.; Diaz-Smoano, M. Arsenic and Selenium Capture by Fly Ashes at Low Temperature. *Environ. Sci. Technol*. **2006**, *40*, 3947–3951.

4. Linak, W.P.; Wendt, J.O.L. Trace Metal Transformation Mechanisms During Coal Combustion. *Fuel Process. Technol*. **1994**, *39*, 173–198.

5. Seames, W.S.; Wendt, J.O.L. Regimes of Association of Arsenic and Selenium During Pulverized Coal Combustion. In *Proceedings of the Combustion Institute*; 2007; Vol. 31.

6. Helble, J.J. A Model for the Air Emissions of Trace Metallic Elements from Coal Combustors Equipped with Electrostatic Precipitators. *Fuel Process. Technol*. **2000**, *63*, 125–147.

7. Li, Y.; Tong, H.; Zhuo, Y.; Wang, S.; Xu, X. Simultaneous Removal of SO_2 and Trace SeO_2 from Flue Gas: Effect of SO_2 on Selenium Capture and Kinetics Study. *Environ. Sci. Technol*. **2006**, *40*, 7919–7924.

8. Miller, S.J.; Ness, S.R.; Weber, G.F.; Erickson, T.A.; Hassett, D.J.; Hawthorne, S.B.; Katrinak, K.A.; Louie, P.K.K. *A Comprehensive Assessment of Toxic Emissions from Coal-Fired Power Plants: Phase I Results from the U.S. Department of Energy Study*; Final Report for the Pittsburgh Energy Technology Center and the U.S. Department of Energy Contract No. DE-FC21-93MC30097 (Subtask 2.3.3); Energy & Environmental Research Center: Grand Forks, ND, Sept 1996.

9. Nyberg, C.M.; Thompson, J.S.; Zhuang, Y.; Pavlish, J.H.; Brickett, L.; Pletcher, S. Fate of Trace Elements HAPs When Applying Mercury Control Technologies. In *Proceedings of the International Conference on Air Quality VI: Mercury, Trace Elements, SO_3, Particulate Matter, and Greenhouse Gases*; Arlington, VA, Sept 24–27, 2007.

10. ADA-ES, Inc. *Field Test Program to Develop Comprehensive Design, Operation, and Cost Data for Mercury Control Systems*; Final Site Report for U.S. Department of Energy National Energy Technology Laboratory Cooperative Agreement No. DE-FC26-00NT41005: Topical Report No. 41005R21; ADA-ES, Inc.: Littleton, CO, March 2005.